PB89-226369

Characterization and Control of Radionuclide Emissions from Elemental Phosphorus Production

Midwest Research Inst., Cary, NC

Prepared for:

Environmental Protection Agency, Research Triangle Park, NC

Feb 89

U.S. Department of Commerce
National Technical Information Service
NTIS

PB89-226369

United States
Environmental Protection
Agency

Office of Air Quality
Planning and Standards
Research Triangle Park NC 27711

EPA-450/3-89-020
February 1989

Air

EPA

Characterization and Control of Radionuclide Emissions From Elemental Phosphorus Production

7

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

EPA-450/3-89-020

Characterization and Control of Radionuclide Emissions From Elemental Phosphorus Production

Emissions Standards Division

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Radiation
Office of Air Quality Planning and Standards
Research Triangle Park, North Carolina 27711
February 1989

PREFACE

Midwest Research Institute (MRI) prepared this report for the U. S. Environmental Protection Agency, Office of Air Quality Planning and Standards on Contract No. 68-02-4379, Work Assignment 12, Ms. Elizabeth Grainger and Mr. Lee Beck served as technical project monitors.

The report was prepared by Mr. Dennis Wallace, Ms. Katy Allen, and Mr. Jim Obremski in MRI's Environmental Engineering Department. Mr. Mark Turner, Mr. Butch Smith, and Ms. Carol Athey provided valuable comments and other members of the Environmental Engineering Department contributed to specific portions of the report.

Approved for:
MIDWEST RESEARCH INSTITUTE

Dennis Wallace for

Roy Neulicht, Program Manager
Environmental Engineering Department

December 12, 1988

TABLE OF CONTENTS

Page

LIST OF FIGURES iv

LIST OF TABLES v

SECTION 1.0 INTRODUCTION 1-1

SECTION 2.0 ELEMENTAL PHOSPHORUS INDUSTRY DESCRIPTION 2-1
    2.1 INDUSTRY CHARACTERIZATION 2-1
    2.2 ELEMENTAL PHOSPHORUS PRODUCTION PROCESSES 2-5
        2.2.1 Process Description 2-5
        2.2.2 Radionuclide Distributions 2-10
    2.3 REFERENCES FOR SECTION 2 2-14

SECTION 3.0 EMISSIONS FROM ELEMENTAL PHOSPHORUS PLANTS 3-1
    3.1 SOURCES OF RADIONUCLIDE EMISSIONS 3-1
    3.2 KILN EMISSION CHARACTERIZATION 3-9
        3.2.1 Mass Emission Rates of Po-210, Pb-210 and PM 3-9
        3.2.2 Acid Gas Emissions 3-17
        3.2.3 Po-210 and Pb-210 Particle Size Distributions 3-17
    3.3 KILN BASELINE EMISSIONS 3-21
    3.4 REFERENCES FOR SECTION 3 3-23

SECTION 4.0 EMISSION CONTROLS 4-1
    4.1 DESCRIPTION OF APPLICABLE CONTROL SYSTEMS 4-2
        4.1.1 Spray Towers 4-2
        4.1.2 Venturi Scrubbers 4-6
        4.1.3 Wet ESP's 4-10
        4.1.4 SD/FF Systems 4-17
        4.1.5 HEPA Filters 4-23
    4.2 PERFORMANCE OF ALTERNATIVE CONTROL TECHNOLOGIES... 4-29
        4.2.1 Venturi Scrubbers 4-30
        4.2.2 Wet ESP's 4-35
        4.2.3 SD/FF Systems 4-38
        4.2.4 HEPA Filters 4-41
    4.3 COST OF CONTROL TECHNOLOGIES 4-41
        4.3.1 Venturi Scrubber Cost Assumptions 4-44
        4.3.2 Wet ESP Cost Assumptions 4-44
        4.3.3 SD/FF Cost Assumptions 4-44
        4.3.4 HEPA Filter Cost Assumptions 4-45
    4.4 REFERENCES FOR SECTION 4 4-47

SECTION 5.0 CONTROL ALTERNATIVE PERFORMANCE AND COST 5-1
    5.1 DEFINITION OF CONTROL ALTERNATIVES 5-1
    5.2 PERFORMANCE OF CONTROL ALTERNATIVES 5-3
    5.3 COSTS OF CONTROL ALTERNATIVES 5-12
    5.4 REFERENCES FOR SECTION 5 5-29

APPENDICES A-E: SEPARATE CBI VOLUME

LIST OF FIGURES

Page

Figure 2-1. General elemental phosphorous plant process flow...... 2-7

Figure 3-1. Vapor pressure curves for Po and Pb.................. 3-4

Figure 3-2. Summary of Po-210 emission data...................... 3-13

Figure 3-3. Summary of Pb-210 emission data...................... 3-14

Figure 4-1. Countercurrent flow spray tower...................... 4-3

Figure 4-2. Venturi scrubber..................................... 4-7

Figure 4-3. Wetted-throat venturi scrubber....................... 4-8

Figure 4-4. Adjustable-throat venturi scrubber................... 4-9

Figure 4-5. Illustration of ESP operating principles............. 4-12

Figure 4-6. Circular-plate type wet ESP.......................... 4-14

Figure 4-7. Flat-plate type wet ESP.............................. 4-15

Figure 4-8. Spray dryer/fabric filter system..................... 4-18

Figure 4-9. Pulse-jet fabric filter.............................. 4-21

Figure 4-10. The HEPA filter performance curve................... 4-25

Figure 4-11. Examples of HEPA filter systems..................... 4-27

Figure 5-1. Capital costs of control alternatives................ 5-17

Figure 5-2. Annualized costs of control alternatives............. 5-18

LIST OF TABLES

Page

TABLE 2-1. PRODUCTION OF ELEMENTAL PHOSHPORUS 1967-1987............ 2-3

TABLE 2-2. USERS OF ELEMENTAL PHOSPHORUS BY-PRODUCT SLAG........... 2-4

TABLE 2-3. OPERATING ELEMENTAL PHOSPHORUS PLANTS, 1988............. 2-6

TABLE 2-4. Po-210 CONCENTRATIONS IN ELEMENTAL PHOSPHORUS PROCESS STREAMS... 2-12

TABLE 2-5. Pb-210 CONCENTRATIONS IN ELEMENTAL PHOSPHORUS PROCESS STREAMS... 2-13

TABLE 3-1. RADIONUCLIDE EMISSIONS FROM ELEMENTAL PHOSPHORUS OPERATIONS.. 3-2

TABLE 3-2. NODULE COOLER EMISSION ESTIMATES........................ 3-6

TABLE 3-3. SUMMARY OF TEST CONDITIONS............................. 3-10

TABLE 3-4. CALCINER PM EMISSION DATA.............................. 3-11

TABLE 3-5. CALCINER RADIONUCLIDE EMISSION DATA..................... 3-12

TABLE 3-6. ACID GAS EMISSION LEVELS............................... 3-18

TABLE 3-7. PARTICLE SIZE DISTRIBUTION BASED ON IMPACTOR SAMPLES.... 3-19

TABLE 3-8 PARTICLE SIZE DISTRIBUTION BASED ON SASS CYCLONE SAMPLES... 3-20

TABLE 3-9. BASELINE Po-210 AND Pb-210 EMISSIONS.................... 3-22

TABLE 4-1. ESTIMATED EFFICIENCY OF MONSANTO SCRUBBER............... 4-34

TABLE 4-2. ESTIMATES OF VENTURI SCRUBBER PERFORMANCE............... 4-36

TABLE 4-3. SUMMARY OF ESP EFFICIENCY CALCULATIONS.................. 4-39

TABLE 4-4. ASSUMPTIONS USED IN ESTIMATING DIRECT AND INDIRECT COSTS... 4-43

TABLE 5-1. PARTICLE SIZE DISTRIBUTIONS FOR Po-210 and Pb-210....... 5-5

TABLE 5-2. ESTIMATED FRACTIONAL EFFICIENCIES FOR VENTURI SCRUBBER CONTROL ALTERNATIVES................................ 5-6

LIST OF TABLES (continued)

Page

TABLE 5-3. ESTIMATED FRACTIONAL EFFICIENCIES FOR WET ESP CONTROL ALTERNATIVES.. 5-7

TABLE 5-4. ESTIMATED PERFORMANCE FOR VENTURI SCRUBBER OPTIONS..... 5-9

TABLE 5-5. ESTIMATED Po-210 EMISSION LEVELS ACHIEVED BY CONTROL ALTERNATIVES.. 5-10

TABLE 5-6. ESTIMATED Pb-210 EMISSION LEVELS ACHIEVED BY CONTROL ALTERNATIVES.. 5-11

TABLE 5-7. REDUCTION OF Po-210 EMISSIONS FROM BASELINE............ 5-12

TABLE 5-8. REDUCTION OF Pb-210 EMISSIONS FROM BASELINE............ 5-13

TABLE 5-9. CAPITAL COST OF CONTROL ALTERNATIVES.................. 5-15

TABLE 5-10. ANNUALIZED COST OF CONTROL ALTERNATIVES................ 5-16

TABLE 5-11. SUMMARY OF COSTS FOR VENTURI SCRUBBER--10 INCH PRESSURE DROP... 5-19

TABLE 5-12. SUMMARY OF COSTS FOR VENTURI SCRUBBER--25 INCH PRESSURE DROP... 5-20

TABLE 5-13. SUMMARY OF COSTS FOR VENTURI SCRUBBER--40 INCH PRESSURE DROP... 5-21

TABLE 5-14. SUMMARY OF COSTS FOR VENTURI SCRUBBER--80 INCH PRESSURE DROP... 5-22

TABLE 5-15. SUMMARY OF COSTS FOR WET WALLS ELECTROSTATIC/ PRECIPITATOR--200 SCA................................ 5-23

TABLE 5-16. SUMMARY OF COSTS FOR WET WALLS ELECTROSTATIC/ PRECIPITATOR--400 SCA................................ 5-24

TABLE 5-17. SUMMARY OF COSTS FOR WET WALLS ELECTROSTATIC/ PRECIPITATOR--600 SCA................................ 5-25

TABLE 5-18. SUMMARY OF COSTS FOR WET WALLS ELECTROSTATIC/ PRECIPITATOR--800 SCA................................ 5-26

TABLE 5-19. SUMMARY OF COSTS FOR SPRAY DRYER/FABRIC FILTER......... 5-27

TABLE 5-20. SUMMARY OF COSTS FOR HEPA FILTRATION SYSTEM............ 5-28

1.0 INTRODUCTION

The U. S. Environmental Protection Agency's (EPA's) Office of Radiation Programs (ORP) is developing a National Emission Standard for Hazardous Air Pollutants (NESHAP) under the authority of Section 112 of the Clean Air Act for radionuclide emissions from elemental phosphorus production facilities. Background information on the elemental phosphorus production processes, radionuclide emissions from these processes, availability of control techniques that could reduce these emissions, and the performance and costs of alternative control techniques is needed to support that regulatory development effort. The ORP will use that background information to define regulatory alternatives and to evaluate the emission reductions, risk levels, and costs associated with each of the regulatory alternatives.

This report presents the results of a study conducted by the Industrial Studies Branch (ISB) in EPA's Office of Air Quality Planning and Standards (OAQPS) that was designed to collect the background information. The specific objectives of the study were to identify the sources of radionuclide emissions, particularly polonium-210 (Po-210) and lead-210 (Pb-210), from elemental phosphorus production; to determine baseline emissions levels of Po-210 and Pb-210 for the key emission sources at each operating elemental phosphorus plant; to identify feasible control alternatives; and to estimate the performance and cost of those control alternatives. Although all potential sources of Po-210 and Pb-210 from elemental phosphorus production were considered, this study focused on Po-210 and Pb-210 emissions from the calcining (or nodulizing operations) because previous studies indicated that those operations are the primary sources of radionuclide emissions from the process. Consequently, this report deals primarily with the characterization and control of Po-210 and Pb-210 emissions from nodulizing calciners or kilns, but other sources of emissions are addressed briefly.

The objectives identified above were addressed through three primary data gathering and analysis tasks. First, all emission data generated by EPA and elemental phosphorus facilities over the past 10 years were compiled and analyzed. As a consequence of these analyses, data gaps were identified, and an emission test program that addressed those gaps was conducted concurrently with this study. The results of that test program are included in this report. Second, plant visits were conducted at each of the five operating facilities to collect data on process and control system operations, process residuals and emissions, and control system performance and cost. Finally, additional information on control system performance and costs was obtained through a literature review, contact with knowledgeable EPA personnel, and telephone contacts with control equipment vendors.

The results of this study are presented in the four sections which follow. Section 2 contains a description of the elemental phosphorus industry. It describes the elemental phosphorus production process and presents data on the distribution of radionuclides in process streams and residues. Section 3 discusses emissions from the elemental phosphorus production process. Sources of radionuclide emissions are identified, and estimates of Po-210 and Pb-210 emissions from the different sources are presented. Detailed information on Po-210, Pb-210, particulate matter (PM), and acid gas emissions from the calcining/nodulizing operation is presented, and baseline estimates of PM and radionuclide emissions from those operations are developed for each operating facility. Section 4 addresses control of calciner/nodulizing kiln radionuclide emissions. Potential control techniques are described, and procedures for estimating the performance and cost of these techniques are presented. Specific control alternatives for calciner operations are defined in Section 5, and estimates of the performance and costs of these alternatives are developed.

2.0 ELEMENTAL PHOSPHORUS INDUSTRY DESCRIPTION

Phosphate rock is the basic raw material used in the production of phosphorus and phosphorus products. About 10 percent of the phosphate rock mined in the U.S. is used in the production of elemental phosphorus, which is produced by a high-temperature reduction process. Environmental releases associated with the elemental phosphorus process include air emissions of criteria pollutants such as particulate matter (PM) and sulfur dioxide (SO_2) as well as the acid gas hydrogen fluoride (HF), liquid effluent streams that have low pH and contain radionuclide materials, and large quantities of slag materials that must be stored or disposed as solid waste. The primary concern of this study is the potential for emission of two radionuclide daughters of uranium-238 (U-238)--polonium-210 (Po-210) and lead-210 (Pb-210)--during the high-temperature operations.

This section briefly describes the elemental phosphorus industry and the elemental phosphorus production processes as a background for understanding radionuclide emission problems and control alternatives. The discussion is divided into two subsections. The first provides an overall description of the industry and identifies operating plants and their capacities. The second describes the elemental phosphorus production process, identifies production and waste streams, and presents the distribution of Po-210 and Pb-210 among those streams.

2.1 INDUSTRY CHARACTERIZATION

Elemental phosphorus is produced from the reaction of phosphate ore with silica and carbon (coke) in a high-temperature electric furnace. The key raw material with respect to both the product and radionuclide emissions is the phosphate ore. Phosphate ore deposits are located principally in three regions of the United States:

1. Southeastern region (mainly Florida, but also South Carolina, North Carolina, and Georgia);
2. Northern Rocky Mountain region (eastern Idaho, western Wyoming, northern Utah, and southwestern Montana); and
3. Middle Tennessee.

Most of the phosphate rock used in this country's phosphate rock and phosphate fertilizer industries is taken from Florida reserves, but most of the ore used in elemental phosphorus production is obtained from the Tennessee and Rocky Mountain regions. The phosphate ores from the three principal regions are distinct in their radiological characteristics. Generally, ores from the southeastern region have the highest radionuclide concentrations, followed respectively by those from the northern Rocky Mountain region and those from middle Tennessee. The radioactivity content of phosphate rocks from different deposits within the same general region, however, may vary widely. Details on the radioactivity levels of the ores used at operating elemental phosphorus plants are presented in Section 2.2.

The principal products of the elemental phosphorus industry are elemental phosphorus and two by-products associated with its production--calcium silicate slag and ferrophosphorus (FeP). The production rates of elemental phosphorus for the years 1967 through 1987 are shown in Table 2-1.[1] Typically, calcium silicate slag is produced at a rate of 8 to 9 Mg per Mg of elemental phosphorus produced, and ferrophosphorus is produced at a rate of 0.1 to 0.3 Mg per Mg of elemental phosphorus produced.[2]

Elemental phosphorus is used primarily in the manufacture of high-grade phosphoric acid, which serves as a feedstock in the production of chemicals and food products. In 1986, 50 percent of the supply was used to produce sodium tripolyphosphate, and small quantities (about 20,000 Mg) were exported.[3] End uses include detergents, metal treatment, foods and beverages, and chemicals.[3]

Historically, the calcium silicate slag produced in this process has been used as an aggregate material. Some of the uses of this material are given in Table 2-2.[2] However, as outlined in Section 2.2.2., this slag may contain Po-210 and Pb-210, and it has been demonstrated to contain U-238. Consequently, concerns have been raised about use of the material. Information collected from plant visits during this study indicates that most slag currently is being stockpiled at plant sites.

The other major by-product is ferrophosphorus. Plant contacts indicated that the market for this product is limited, but some is sold in

TABLE 2-1. PRODUCTION OF ELEMENTAL PHOSPHORUS 1967-1987[1]

Year	Production, Mg (tons)	Year	Production, Mg (tons)
1987	312,117 (343,329)	1975	408,642 (449,506)
1986	330,652 (363,717)	1974	476,523 (524,175)
1985	326,582 (359,196)	1973	477,748 (525,523)
1984	350,966 (386,063)	1972	490,990 (540,089)
1983	332,772 (366,050)	1971	495,535 (545,089)
1982	328,354 (361,189)	1970	542,323 (596,555)
1981	387,334 (426,067)	1969	566,347 (622,982)
1980	392,482 (431,730)	1968	557,585 (613,343)
1979	417,765 (459,541)	1967	533,642 (587,006)
1978	401,158 (441,274)		
1977	391,174 (430,291)		
1976	396,959 (436,655)		

TABLE 2-2. USES OF ELEMENTAL PHOSPHORUS BY-PRODUCT SLAG[2]

Neutralizer for acidic soils
Road ballast
Manufacture of Portland cement
Manufacture of slag concrete blocks
Slag wool as thermal insulation
Ceramic bodies and glazes
Railroad ballast and roadbeds
Fill for septic tank drainage fields
Roadway, substation, and soil stabilization at commercial facilities and utility installations
Municipal sewage plant filter beds
Aggregate for parking lot and driveway paving
Built-up roofing aggregate

specialty markets such as specialty steels, cast alloys, and paint pigments. One plant sells the ferrophosphorus to a plant that processes it to recover vanadium.

In 1980, eight elemental phosphorus plants were operating in the U.S. However, since that time, the two Florida plants, Mobil in Pierce and Stauffer in Tarpon Springs, have shut down as a result of high electrical costs in that State. Recently, Monsanto dismantled its facility in Columbia, Tennessee. Consequently, only five plants currently are operating, and this number is not expected to increase in the foreseeable future. Table 2-3 identifies the five operating plants and presents estimates of their operating capacities for phosphorus production and of the quantity of phosphate ore that would be required to produce this capacity. The estimates are based on quantities published by EPA in 1983.[2] During plant visits performed during July and August 1988, industry personnel indicated that capacities had not changed since 1983. They also indicated that production rates vary from 50 to 100 percent of capacity depending upon market demand.

2.2 ELEMENTAL PHOSPHORUS PRODUCTION PROCESSES

2.2.1 Process Description

Elemental phosphorus is produced by a thermal process that uses silica as a fluxing agent for the calcium present in phosphate feed ore. Phosphate is reacted with silica and coke in a reducing atmosphere to form elemental phosphorus (P_4), CO, and calcium silicate slag. In addition, by-product FeP is formed from the reaction of elemental phosphorus with coke and iron oxide. Simplified equations for the process are:[2]

$$4\ \underset{\text{(ore)}}{Ca_5F(PO_4)_3} + 18\ SiO_2 + 30\ C \rightarrow 18\ \underset{\text{(slag)}}{CaO \cdot SiO_2 \cdot 1/9\ CaF_2} + 30\ CO\uparrow + 3P_4\uparrow \qquad (1)$$

$$2\ P_2O_5 + 10\ C \rightarrow 10\ CO\uparrow + P_4\uparrow \text{ (intermediate reaction)} \qquad (2)$$

$$2\ Fe_2O_3 + 6C + P_4 \rightarrow 4\ FeP + 6\ CO\uparrow \qquad (3)$$

Figure 2-1 presents a simplified process flow diagram that generally represents the process used at the five operating plants. The paragraphs

TABLE 2-3. OPERATING ELEMENTAL PHOSPHORUS PLANTS, 1988

Plant	Phosphorus capacity, 10^3 Mg/yr (10^3 tons/yr)	Ore requirements, 10^3 Mg/yr (10^3 tons/yr)
FMC Corporation, Pocatello, Idaho	123 (135)	1,470 (1,620)
Monsanto Co., Soda Springs, Idaho	95 (105)	1,000 (1,100)
Stauffer Chemical Co., Silver Bow, Mont.	38 (42)	380 (420)
Stauffer Chemical Co., Mt. Pleasant, Tenn.	41 (45)	440 (480)
Occidental Chemical Co., Columbia, Tenn.	45 (50)	490 (540)

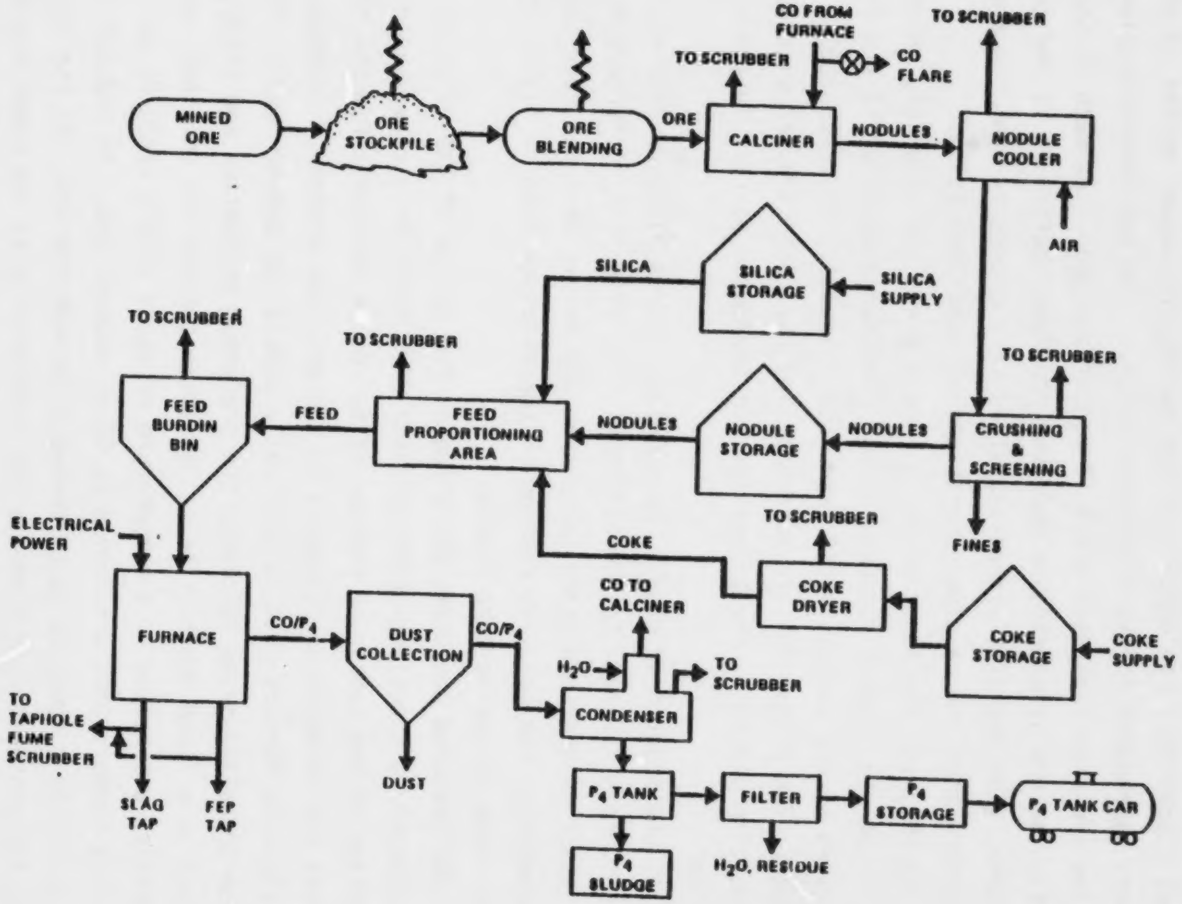
MINED ORE
ORE STOCKPILE
ORE BLENDING
ORE
TO SCRUBBER
CO FROM FURNACE
CO FLARE
CALCINER
NODULES
TO SCRUBBER
NODULE COOLER
AIR
SILICA
SILICA STORAGE
SILICA SUPPLY
TO SCRUBBER
TO SCRUBBER
TO SCRUBBER
FEED BURDIN BIN
FEED
FEED PROPORTIONING AREA
NODULES
NODULE STORAGE
NODULES
CRUSHING & SCREENING
FINES
TO SCRUBBER
COKE
COKE DRYER
COKE STORAGE
COKE SUPPLY
ELECTRICAL POWER
FURNACE
CO/P4
DUST COLLECTION
CO/P4
CO TO CALCINER
H2O
TO SCRUBBER
CONDENSER
TO TAPHOLE FUME SCRUBBER
SLAG TAP
FEP TAP
DUST
P4 TANK
FILTER
P4 STORAGE
P4 TANK CAR
P4 SLUDGE
H2O, RESIDUE

Figure 2-1. General elemental phosphorus plant process flow.

below describe the major components of this process and identify points in the process where operations differ significantly among the plants.

Phosphate ore is mined offsite and is shipped by rail or truck to each of the five plants for processing. The three western plants receive their ore from Idaho mines that operate about 7 months per year. These plants stockpile large amounts of ore during the summer months to continue process operations during the winter months. The two Tennessee plants receive ore from Tennessee mines 12 months per year. At each of the plants, the ore is stockpiled and then processed before it is fed to the calciner. The specific processing steps vary depending upon the ore characteristics and calciner operations as described below.

At FMC, the ore is screened to remove oversized material, which is sent to an ore crusher for processing. The screened material and fines generated by the process are formed into briquettes by briquette presses. The briquettes are screened, and the fines are recycled to the briquetting process. The briquettes are then used as feed to the calciner.

At the other four plants, as-received ore is blended with recycled fines to form the feed to the calciner. The principal difference in the facilities is that the Tennessee plants use an ore that has been washed. Consequently, the moisture content of the calciner feed is higher at these plants than at the western plants.

The prepared phosphate ore blend is fed to one of two types of "calciners"--a traveling-grate calciner (FMC only) or a rotary kiln. The objective of the calcining process is to remove moisture from the ore, combust any volatile constituents in the ore, and produce a feedstock for the electric furnace that is physically stable and appropriately sized. In the traveling-grate calciner, the preformed briquettes are placed in pallets to a fixed depth. The pallets move through the calciner, and the briquettes are heated to a temperature of about 1300°C (2400°F) by overfire burners that are fueled by CO or natural gas. An induced draft fan pulls the combustion gases downward through the bed. In the rotary kiln, the phosphate ore blend is fed continuously to the upper end of the kiln. As the ore moves through the kiln, moisture and volatiles are driven off, and the remaining material is heated to a temperature of about

1300°C (2400°F) by combustion gases that flow through the kiln countercurrent to the ore. At those temperatures, the ore is heated to its incipient melting point, and the tumbling action of the kiln agglomerates the material into larger nodules. Typically, the kilns have a solids residence time of about 4 h. The kilns are fueled by a combination of CO, coal, and natural gas.

Both types of calciners generate large quantities of high-temperature combustion gases. Volumetric flows for the calciners currently operating range from about 3,700 to 11,000 m^3/min (130,000 to 400,000 acfm) at temperatures in the range of 320° to 430°C (600° to 800°F). Two of the five plants use a waste heat boiler for energy recovery. The gases from the kiln or boiler are treated in an air pollution control system before they are discharged to the atmosphere. The air pollution control systems for the five plants are described in Section 4. Details on the combustion gas characteristics and kiln operating rates are presented in Appendices A through E.

The nodules or briquettes that leave the calciner are air cooled and subjected to crushing and sizing operations. Materials that are approximately 1.5 to 2.5 cm (0.6 to 1.0 in.) in diameter are sent to the feed proportioning area for the electric furnace. Undersized material is recycled to the ore blending area and subsequently through the calciner.

The nodulized or briquetted phosphate feed material is sent to a proportioning area where it is mixed with sized coke and silica to obtain the required weight proportion of furnace feed (burden). A proper ratio of SiO_2 to CaO is required to form slag with the necessary flow properties to facilitate removal from the furnace. Coke is added as a carbon source to reduce the intermediate reaction product P_2O_5 to elemental phosphorus. This proportioned furnace feed burden is conveyed to the furnace burden bins.

The electric furnace is a large chamber lined with carbon blocks in the lower section. Three consumable carbon electrodes extend through the roof to conduct the electric current. An electric arc is formed between the electrodes and the furnace lining. The burden material is gravity fed continuously to the top of the furnace from where it progresses downward until it is heated and eventually melts in the intense heat of the electric arc. At the heat source, the maximum temperature can reach 4400°C (7950°F). At 1400° to 1800°C (2550° to 3270°F), silica becomes a strong acid that reacts with the calcium phosphate to yield a calcium silicate slag and P_2O_5. The P_2O_5 in turn reacts with the carbon in the coke and is reduced to CO and P_4.[2]

The elemental phosphorus is driven off as a vapor in the CO off-gas stream. The slag and ferrophosphorus continually collect in the bottom of the furnace in molten layers with the denser ferrophosphorus layer below the slag layer. Periodically, these molten by-products are tapped separately. Slag is tapped approximately once each hour and ferrophosphorus up to several times each day. The slag and ferrophosphorus are air cooled in a pit and stockpiled for later use.

At three of the five facilities, the furnace product gases are treated for dust removal in an electrostatic precipitator (ESP). At the other two facilities, the gas stream is routed directly to the phosphorus recovery processes. The gas stream from the ESP, or from the furnace at those plants that do not have an ESP, are sent to water spray condensers where the gases are cooled and the phosphorus is condensed to a liquid. The condensed phosphorus is collected under water, purified by filtering, and then pumped to underwater storage. The gas stream from the condenser is primarily CO. Essentially all of the phosphorus-free CO is recycled to fuel the nodulization process. The remaining CO is recycled to other plant operations or exhausted through flare stacks. Plant personnel indicated that CO is flared only on days when the kiln is not operating.

2.2.2 Radionuclide Distributions

The primary objective of this study is to evaluate Po-210 and Pb-210 emissions from elemental phosphorus plants (particularly from the nodulizing kiln or calciner) and to develop alternatives for the control of these emissions. Consequently, the distribution of Po-210 and Pb-210 among the different process streams is of interest. The paragraphs below summarize the information that has been collected on these distributions. This information is based on comprehensive studies of elemental phosphorus production conducted for EPA prior to 1983, test data developed by EPA in 1983 and 1984, and data supplied by the plants during earlier EPA studies and during site visits conducted for this study.

Both Po-210 and Pb-210 are volatile metals. As such, it is quite likely that they will be volatilized in the calciner and leave the calciner with the combustion gas stream. However, data from the five operating facilities indicate that at least some of the Po-210 and Pb-210 remains in the nodules that are fed to the electric furnace. Plant environmental personnel and industry research personnel contacted during this study all agreed that any Po-210 and Pb-210 that does reach the electric furnace would be volatilized and returned to the kiln with the CO. Available data generally support this conclusion, but limited data from the EPA facility studies indicate that some Po-210 and Pb-210 is deposited in the slag.[2] However, these data should be viewed with caution because slag streams are difficult to sample and analyze and because Po-210 and Pb-210 concentrations in the slag depend on the age of the slag. This age dependence results from decay of other radiouclides that are known to be present in the slag.

Tables 2-4 and 2-5 summarize available data on Po-210 and Pb-210 in elemental phosphorus streams. These data generally suggest that most Po-210 and Pb-210 concentrates in the kiln exhaust stream, but they do not demonstrate conclusively that this stream is the only pathway for these constituents. In particular, they indicate that significant quantities of Po-210 and Pb-210 remain in the slag in some cases. During plant visits, plant personnel indicated that these levels appear to overestimate the quantities of radionuclides in the slag. Monsanto research personnel indicated that slag sampling was difficult, and accurate values could not be obtained.[16] However, they estimate that Po-210 concentrations in the slag are about 5 to 10 pCi/g.

TABLE 2-4. Po-210 CONCENTRATIONS IN ELEMENTAL PHOSPHORUS PROCESS STREAMS

	Po-210 concentrations, pCi/g					
	FMC, Idaho	Monsanto, Idaho	Stauffer		Occidental, Tenn.	Monsanto, Tenn.
Process stream			Mont.	Tenn.		
Ore	22[a] 21[g] 23[j] 23[k]	91[b] 126[h]	36[c] 40[i]	3.5[d]	4.1[e]	4.1[f]
Nodules	<2.6[a] 8[g] 9.8[j]	1.9[b]	4[i]	0.09[l]		3.3[f]
Slag	<16[a]		<2[c] (fresh) 2.7[c] (piled)	0.4[d]		<0.8[f]
Ferrophosphorus	<0.6[a]		<1.9[c]	0.05[d]		1.0[f]
Inlet PM	2,500[g] 2,600[m] 4,400[k]	1,920[n]	3,400[i]			
Stack PM	19,000[g] 25,000[m] 53,000[k]	37,000[b] 5,000[n] 35,000[h]	37,000[i]		1,200[o]	

[a] Based on EPA test data collected in 1977 as presented in Reference 4.

[b] Based on EPA test data collected in 1984 as presented in Reference 5; includes combined ore and recycle feed.

[c] Based on EPA test data collected in 1982 as presented in Reference 6.

[d] Based on data supplied to EPA by facility as presented in Reference 2.

[e] Data presented in Reference 2. Concentrations assumed to be equal to those measured at the Monsanto, Tennessee, facility in 1982 as presented in Reference 7.

[f] Based on EPA test data collected in 1982 as presented in Reference 7.

[g] Based on test data collected by EPA in 1984 as presented in Reference 8.

[h] Based on EPA test data collected in 1988 as presented in Reference 9.

[i] Based on test data collected by EPA in 1984 as presented in Reference 10.

[j] Based on data supplied to MRI by facility during 1988 site visit and reported in Reference 11. Nodule estimates based on average of three measurements made through bed; values ranged from 5.8 to 14.9.

[k] Based on EPA test data collected in 1988 as presented in Reference 12.

[l] Based on data supplied to MRI by facility during 1988 plant visit as reported in Reference 13.

[m] Based [illegible] emission test data collected by the facility in 1985 through 1987 as reported in Reference 11.

[n] Based on emission test data collected by the facility in 1988 as reported in Reference 14.

[o] Based on data supplied to MRI by the facility during 1988 plant visit as reported in Reference 15.

TABLE 2-5. Pb-210 CONCENTRATIONS IN ELEMENTAL PHOSPHORUS PROCESS STREAMS

Process stream	Pb-210 concentrations, pCi/g					
	FMC, Idaho	Monsanto, Idaho	Stauffer		Occidental, Tenn.	Monsanto, Tenn.
			Mont.	Tenn.		
Ore	27^{a} 26^{g} 24^{k}	150^{b} 127^{h}	38^{c} 46^{i}	4.2^{d} 4.2^{j}	4.2^{e}	4.2^{f}
Nodules	18^{a} 27^{g}	5.6^{b}	7^{i}	2.8^{j}		7.2^{f}
Slag	11^{a}		$<1^{c}$ (fresh) 1.8^{c} (piles)	0.3^{d} 0.17^{i}		1.5^{f}
Ferrophosphorus	1.1^{a}		0.7^{c}	0.1^{d}		3.9^{f}
Inlet PM	33^{g} 180^{k}		$2,900^{i}$			
Stack PM	240^{g} 710^{k}	$9,700^{b}$ $8,200^{h}$	$4,600^{i}$			

[a] Based on EPA test data collected in 1977 as presented in Reference 4.
[b] Based on EPA test data collected in 1984 as presented in Reference 5; includes sample collected from combined ore/recycle feedstock to kiln.
[c] Based on EPA test data collected in 1982 as presented in Reference 6.
[d] Based on data supplied to EPA by facility as presented in Reference 2.
[e] Ore concentration based on data presented in Reference 2 under the assumption that ore characteristics are comparable to those found at Monsanto (Reference 7).
[f] Based on EPA test data collected in 1982 as presented in Reference 7.
[g] Based on test data collected by EPA in 1984 as presented in Reference 8.
[h] Based on data collected by EPA in 1988 as presented in Reference 9.
[i] Based on test data collected by EPA in 1984 as presented in Reference 10.
[j] Based on data supplied to MRI by facility during 1988 plant visit as presented in Reference 13.
[k] Based on data collected by EPA in 1988 as presented in Reference 12.

2.3 REFERENCES FOR SECTION 2

1. Bureau of Census, U. S. Department of Commerce. Current Industrial Reports: Inorganic Chemicals. Washington, D.C. 1968-1987.

2. Stula, R. T., R. E. Balanger, C. L. Clary, R. F. May, M. E. Spaeth, and J. P. Swenson. Airborne Emission Control Technology for the Elemental Phosphorus Industry, Final Report for EPA Contract No. 68-01-6429. Science Applications, Inc. La Jolla, California. January 1984.

3. U. S. Department of the Interior, Preprint from the 1985 Minerals Yearbook: Phosphate Rock. Pittsburgh, Pennsylvania. 1986.

4. Eadie, G. and D. Bernhardt. Radiological Surveys of Idaho Phosphate Ore Processing--The Thermal Process Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada. Technical Note ORP/LV-77-3. November 1977.

5. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: Monsanto Plant, Soda Springs, Idaho. Washington, D.C. September 1984.

6. Andrews, V. Emissions of Naturally Occurring Radioactivity: Stauffer Elemental Phosphorus Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada. Publication No. EPA-520/6-82-019. November 1982.

7. Andrews, V. Emissions of Naturally Occurring Radioactivity: Monsanto Elemental Phosphorus Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada, Publication No. EPA-520/6-82-021. November 1982.

8. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: FMC Plant, Pocatello, Idaho. Washington, D.C. June 1984.

9. Radian Corporation. Draft Final Emission Test Report, Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

10. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: Stauffer Plant, Silver Bow, Montana. Washington, D.C. August 1984.

11. Memo and attachments from Wallace., D., and K. Leeds, Midwest Research Institute, to Beck, L., EPA/ISB. August 9, 1988. Site Visit--FMC Corporation, Pocatello, Idaho.

12. Radian Corporation. Draft Final Emission Test Report, FMC Elemental Phosphorus Plant, Pocatello, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

13. Memo and attachments from Wallace, D., and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 23, 1988. Site Visit--Stauffer Elemental Phosphorus Plant, Mount Pleasant, Tennessee.

14. Memo and attachments from Wallace D., and K. Leeds, Midwest Research Institute, to Beck, L., EPA/ISB. August 9, 1988. Site Visit--Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho.

15. Memo and attachments from Wallace, D., and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 23, 1988. Site Visit--Occidental Elemental Phosphorus Plant, Columbia, Tennessee.

16. Telecon. Wallace, D., Midwest Research Institute, with Abbot, D., Monsanto Chemical Company. July 12, 1988. Radionuclides in Phosphorus Process Streams.

3.0 EMISSIONS FROM ELEMENTAL PHOSPHORUS PLANTS

The primary objectives of this study are to estimate current emission rates of the radionuclides Po-210 and Pb-210 from elemental phosphorus plants and to evaluate control measures for those emissions. This section identifies potential sources of Po-210 and Pb-210 emissions, presents estimates of emission levels, and provides information on the characteristics of the emissions as a basis for the control technology assessments that are presented in Sections 4 and 5. The discussion addresses the different sources of radionuclide emissions within the elemental phosphorus process, but it focuses on emissions from the calcining (or nodulizing) operation because emissions from the calciner are much greater than those from all other plant operations combined. The three sections below provide a brief discussion of the different emission sources and the estimated levels of emissions from these sources, discuss calciner emissions in detail, and present estimates of baseline emissions for calcining operations at the five operating facilities.

3.1 SOURCES OF RADIONUCLIDE EMISSIONS

The Po-210 and Pb-210 concentration data presented in Section 2.2.2 indicated that these radionuclides are present at significant levels in three elemental phosphorus production streams--the ore feed, calcined nodules, and slag from the electric furnaces. If the processing, handling, or storage of these process streams generates particulate matter (PM) emissions, then Po-210 and Pb-210 are emitted to the atmosphere. The operations that result in emissions include high-temperature furnaces (specifically the calciner and the electric furnaces); nodule cooling, crushing, and screening; and transfer and storage of ore, nodules, slag, electric furnace ESP catch, and calciner air pollution control device (APCD) catch. The paragraphs below briefly describe each of these sources and present preliminary estimates of the levels of Po-210 and Pb-210 emissions from these sources. Table 3-1 provides a summary of these preliminary estimates for the different sources as a means of comparing the relative levels of emissions from those sources. These estimates are based on information collected by EPA surveys and sampling programs that were conducted in support of the 1983 NESHAP proposal.[1-3] More detailed

TABLE 3-1. RADIONUCLIDE EMISSIONS FROM ELEMENTAL PHOSPHORUS OPERATIONS

	Emissions, Ci/yr					
	Po-210			Pb-210		
Storage and handling operations	FMC, Idaho[1]	Monsanto, Tenn.[2]	Stauffer, Mont.[3]	FMC, Idaho[1]	Monsanto, Tenn.[2]	Stauffer, Mont.[3]
Nodulizing kiln	6.9	0.75	0.20	0.003	0.48	0.28
Nodule coolers	0.2	Neg.	0.003	0.001	Neg.	Neg.
Electric furnace	0.31	0.015	0.003	0.005	0.001	0.001
Nodule crushing/screening	NA	Neg.	Neg.	NA	Neg.	Neg.
Storage and handling operations						
Ore	NA	NA	Neg.	NA	NA	Neg.
Nodules	NA	Neg.	Neg.	NA	Neg.	Neg.
Slag	NA	NA	NA	NA	NA	NA
ESP catch	NA	NA	0[a]	NA	NA	0[a]
Kiln APCD catch	NA	NA	NA	NA	NA	NA

[a] System does not include ESP.
Neg. = <0.001.
NA = Not available.

information on calciner emission rates is presented in Section 3.2. No additional data on emissions from sources other than the calciner were identified during this study.

The principal source of Po-210 and Pb-210 emissions from elemental phosphorus production is the nodulizing kiln or calciner. Emissions from the calciner are generated via three mechanisms. First, both Po-210 and Pb-210 are relatively volatile metals as evidenced by the vapor pressure curves shown in Figure 3-1.[4,5] The horizontal axis of the curve indicates temperature and the vertical axis indicates the partial pressure of the Pb-210 and Po-210 at temperature. The maximum concentration that the metal can achieve in vapor phase is the ratio of the partial pressure to 760 mmHg. At the temperatures reached in the calciner/kiln ore bed (-1300°C), significant quantities of Po-210 and Pb-210 are volatilized and exit the kiln as vapor in the combustion gas stream. These vapor-phase metals generally condense on surfaces of PM that is entrained in the combustion gas before they penetrate the air pollution control system. Second, as the combustion gases are drawn through the ore bed of the moving grate-calciner or the tumbling ore in a kiln, relatively large quantities of PM are entrained in the combustion gas stream. These entrained particles, which contain Po-210 and Pb-210, also are exhausted from the calciner with the combustion gases. Third, Po-210 and Pb-210 can be volatilized in the electric furnace and returned to the kiln in the CO fuel stream. The Po-210 and Pb-210 again will leave the kiln as vapor and condense on PM surfaces downstream from the kiln.

Data on the relative concentrations of Po-210 and Pb-210 in the ore feed and nodule product were collected by EPA at three facilities.[6-8] These data indicate that on a mass basis assuming the nodule mass flux is about 80 percent of the ore mass flux, less than 10 percent of the Po-210 and 20 to 60 percent of the Pb-210 are retained in the nodules for rotary kiln operations. For the moving grate calciner, about 30 percent of the Po-210 and almost all of the Pb-210 remain in the nodules. These losses represent the quantity of material lost to the calciner/kiln combustion gases via the first two mechanisms. No data on the quantity of Po-210 and Pb-210 that return to the calciner/kiln with the CO were identified during this study. However, the quantities are expected to be relatively small

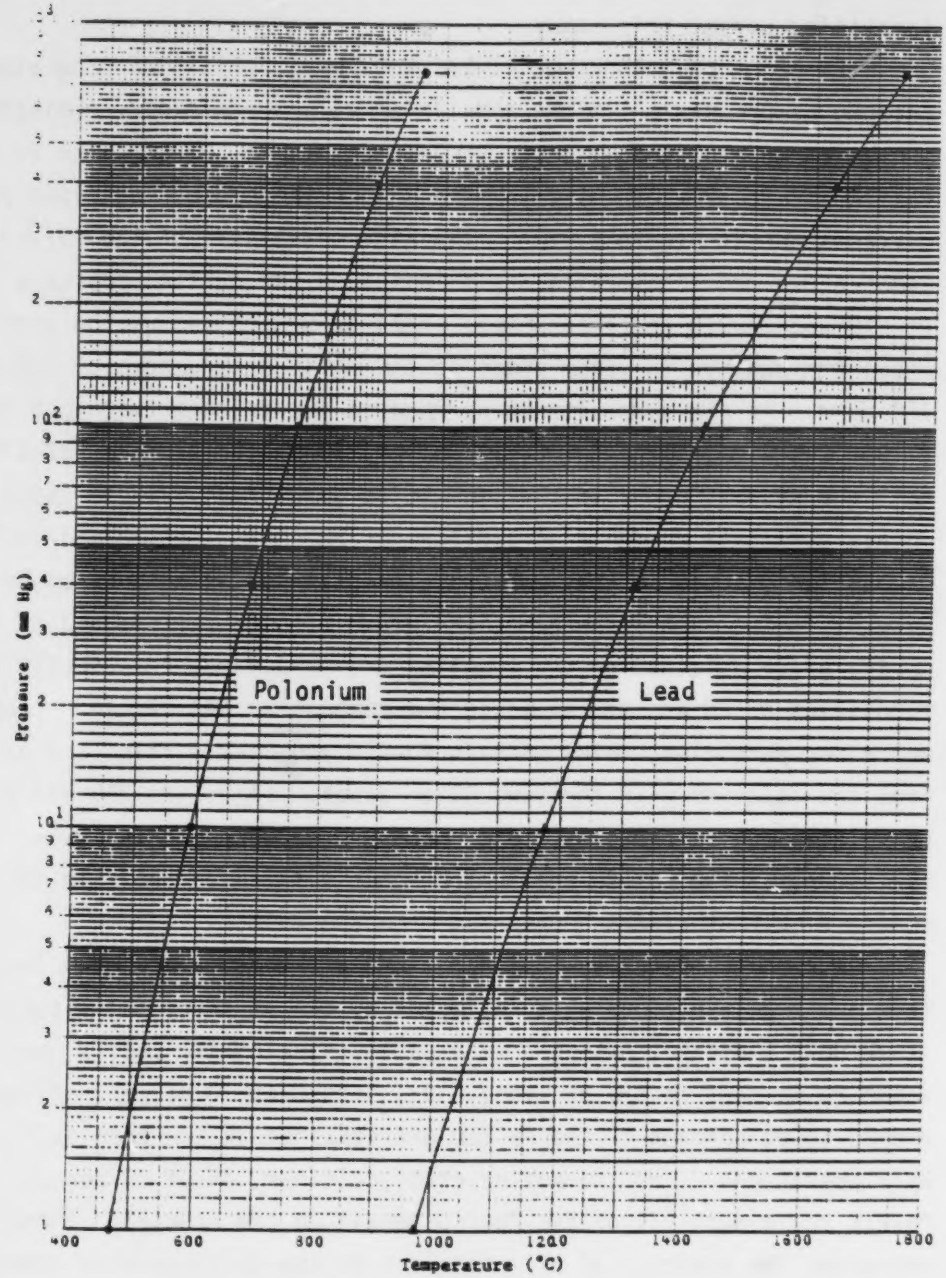

Figure 3-1. Vapor pressure curves for Po and Pb.

because of the cleaning/condensation process used to remove dust and phosphorus from this stream. Table 3-1 presents preliminary estimates of the total quantities of Po-210 and Pb-210 that are emitted from the nodulizing kiln or calciner.[1-3,9] These estimates are based on limited test data and on control levels in place before 1983 and will be updated in Section 3.2. However, they do serve to compare the relative magnitude of calciner emissions to emissions from other processes.

Nodules are discharged from the calciner/kiln to the nodule cooler where they are air cooled. The high-velocity airflow in the coolers results in entrainment of PM, which contains Po-210 and Pb-210. However, data generated by EPA, which are presented in Table 3-1, indicate that with the exception of emissions generated at FMC, these emissions are negligible in comparison to calciner emissions. These data are supported by the emission estimates shown in Table 3-2, which are based on the PM emission limits that States have established for nodule cooling emissions and the concentrations of Po-210 and Pb-210 that have been measured in nodules.[6-8,10] These estimates are based on the assumption that Po-210 and Pb-210 are uniformly distributed throughout the calcined nodules. This assumption is likely to produce conservatively high estimates because volatilization in the calciner or kiln will deplete Po-210 and Pb-210 near nodule surfaces. These surface materials are more likely to be eroded and entrained during cooling. The differences at FMC may result from the high temperature of the cooler exhaust which is estimated to be in the 200° to 300°C (400° to 600°F) range. It is possible that Po-210 could be volatilized from the nodule bed in the cooler and that a portion of the volatilized material could be emitted as a vapor at the exhaust gas temperatures.

The nodules are removed from the cooler and subjected to crushing and screening operations to generate a feed that is sized appropriately for the electric furnace. Again, fugitive PM emissions from these operations can contain Po-210 and Pb-210. However, the data in Table 3-1 indicate that emissions of Po-210 and Pb-210 from crushing and screening operations are estimated to be less than 0.001 Ci/yr at each of the three plants tested by EPA.

TABLE 3-2. NODULE COOLER EMISSION ESTIMATES

Facility	Allowable PM, lb/h[10]	Nodule activity level, Ci/g[6-8]		Estimated emissions, Ci/yr	
		Po-210	Pb-210	Po-210	Pb-210
FMC	83	8	27	0.003[a]	0.009[a]
Monsanto	31	1.9	5.6	<0.001	0.001
Stauffer	12	4	7	<0.001[a]	<0.001

[a] Note that these emission levels are lower than those measured by EPA in earlier studies as reported in References 1 and 3.

The final processing step that is a potential source of Po-210 and Pb-210 emissions is the electric furnace. The Po-210 and Pb-210 that enter the furnace with the nodules are partitioned among four discharge streams--slag, ferrophosphorus, primary phosphorus/CO gas stream, and fugitive emissions from furnace tapholes. The data presented in Section 2.2.2 indicate that of the total Po-210 that enters the plant with the ore, 5 to 60 percent is contained in the slag and less than 0.1 percent is contained in the ferrophosphorus. For Pb-210, the percentages range from 20 to 60 percent and less than 0.1 percent for slag and ferrophosphorus, respectively. Plant personnel contacted during site visits indicated that these estimated Po-210 concentrations are higher than the concentrations that they would expect to remain in the slag given the high temperatures reached in the furnace. Also, as described in Section 2, radionuclides in the slag are difficult to sample and analyze, and the concentrations that were reported have large uncertainties. Consequently, the information on distribution of Po-210 and Pb-210 is not considered to be reliable.

The Po-210 and Pb-210 that are emitted from the tapholes may be captured by localized hoods and collected by the emission control system, or they may be emitted to the atmosphere through furnace shop windows, doors, and roof monitors. No data are available on the quantities that are collected by the emission control system. However, the data in Table 3-1 indicate that as much as 0.31 Ci/yr of Po-210 and 0.005 Ci/yr of Pb-210 are emitted from the furnaces. Note that these levels are quite small in comparison to kiln emissions. The Po-210 and Pb-210 that are entrained in the phosphorus/CO stream can be collected in the ESP (if one is used), condensed with the phosphorus, or returned to the kiln with the CO. Plant personnel had no data on the radionuclide content of the ESP dust but did indicate that virtually no radionuclides were collected with the phosphorus. The kiln emission rates account for any Po-210 or Pb-210 that returns to the kiln with the CO.

Fugitive PM emissions from transfer and storage of ore, nodules, and waste streams also can be a source of Po-210 and Pb-210. The only storage and transfer operations for which emission data are available are those related to nodule handling. Generally, these operations are enclosed, and emissions are controlled by hooding systems with collection in scrubbers or baghouses. Measurements conducted by EPA prior to 1983 indicate that emissions from these operations are less than 0.001 Ci/yr for each of the five plants. Generally, emissions from ore handling and kiln air pollution control device catch handling also can be assumed to be negligible because all plants currently use some type of wet collection, and the moisture in these streams will limit fugitive emissions. No data were identified on the level of emissions from the handling of slag or ESP catch. However, the data on plant production rates, slag generation rates, and radionuclide concentrations in the slag presented in Section 2.0 were used to generate "worst-case" estimates of Po-210 and Pb-210 emission rates from slag handling. These emission estimates were obtained by multiplying the activity levels in the slag (see Tables 2-4 and 2-5) by the annual PM emission rates determined from the following equations for material handling (Eq. 3-1) and wind erosion from active storage areas (Eq. 3-2):[11]

$$E_1 = 1.18\text{x}10^{-3} \frac{(U/2.2)^{1.3}}{(M/2)^{1.4}} \cdot 9W \qquad (3\text{-}1)$$

where

E_1 = materials handling PM emissions, kg/yr

U = mean wind speed, m/s

M = material moisture content, percent

W = plant P_4 production capacity, Mg/yr

and

$$E_2 = 2.82\text{x}10^2 (\frac{S}{1.5})(\frac{365-P}{235})\frac{f}{15} \qquad (3\text{-}2)$$

where

E_2 = emissions from wind erosion, kg/yr/acre

S = silt content of slag, percent

P = percentage of days with $\geq$0.25 mm precipitation per year

f = percentage of time wind exceeds 5.4 m/s

As a worst case the mean wind speed was assumed to be 15 m/s, the material moisture content 0.25 percent, the silt content 10 percent, the percentage of time the wind exceeds 5.4 m/s 100 percent, and the percentage of days with precipitation 0 percent. Under these worst-case scenarios, all plants are estimated to have Po-210 and Pb-210 emissions of less than 0.003 Ci/yr for materials handling and less than 0.0003 Ci/acre/yr for wind erosion.

3.2 KILN EMISSION CHARACTERIZATION

As indicated by the information presented in Section 3.1, the nodulizing kiln (or calciner) is by far the greatest source of Po-210 and Pb-210 emissions from elemental phosphorus production. Consequently, control technology analyses presented in Section 4.0 focus on this emission source. This section provides a comprehensive review of available calciner emission data. It is divided into three subsections. The first presents information on Po-210, Pb-210, and PM emission rates. The second discusses acid gas emissions from the calcining operation, and the third presents data on Po-210 and Pb-210 particle size distributions.

3.2.1 Mass Emission Rates of Po-210, Pb-210 and PM

The emissions of PM and radionuclides from elemental phosphorus plant calcining operations have been tested extensively by both EPA and the facilities since 1977. Data are available for four of the five operating facilities. Although these tests provide a firm basis for regulating radionuclide emissions, evaluation of the data to identify general emission trends is complicated by the plant-to-plant variations in processes and air pollution control systems and by the inherent uncertainties that result from complex sampling situations (high moisture, high temperature, and cyclonic flows) and radionuclide analytical techniques. The available test data are summarized in Tables 3-3 through 3-5. Table 3-3 identifies test locations and presents information on stack gas conditions. Table 3-4 presents PM emission rates and concentrations, and Table 3-5 presents Po-210 and Pb-210 emission concentrations and annual emission rates.

Figures 3-2 and 3-3 present a more detailed summary of the emission concentration data for Po-210 and Pb-210, respectively. In each figure, run-specific emission concentrations are presented for the test series that are summarized in Table 3-5. The data are grouped into one of four levels of control--no control, low-energy scrubber, venturi scrubber, and

TABLE 3-3. SUMMARY OF TEST CONDITIONS[a]

						Test conditions				
						Volumetric flow		Temperature		
Test ID	Facility	Unit tested	Air pollution control	Test date	Test sponsor	m^3/min	acfm	°C	°F	Moisture, percent
A	FMC, Idaho[b]	Calciner 2-1	None	1983	EPA[c]	4,020	142,000	290	550	9.5
B		Calciner 2-2	None	1983	EPA[c]	5,210	184,000	280	530	9.9
C		Calciner 2-2	Slinger scrubber/cyclonic mist eliminator	1983	EPA[c]	3,550	125,000	62	140	15.4
D		Calciner 1-1	Slinger scrubber/cyclonic mist eliminator	1983	EPA[c]	3,220	114,000	59	139	20.8
E		Calciner 1-2	Slinger scrubber/cyclonic mist eliminator	1983	EPA[c]	2,620	92,500	58	136	20.7
F		Calciner 2-1	Slinger scrubber/cyclonic mist eliminator	1985	FMC[d]	2,360[e]	83,300[e]	NA	NA	NA
G		Calciner 2-2	Slinger scrubber/cyclonic mist eliminator	1985	FMC[d]	2,340[e]	82,500[e]	NA	NA	NA
H		Calciner 2-1	Slinger scrubber/cyclonic mist eliminator	1987	FMC[f]	3,870	137,000	54	130	17.7
I		Calciner 2-2	Slinger scrubber/cyclonic mist eliminator	1987	FMC[f]	3,880	137,000	54	130	17.7
J		Calciner 1-1	Low-energy venturi/horizontal chevron-blade mist eliminator	1987	FMC[f]	2,890	102,000	54	129	15.5
K		Calciner 1-2		1987	FMC[f]	3,830	135,000	49	121	13.9
L	Monsanto, Idaho	Kiln	Spray tower	1983	EPA[g]	8,070	285,000	68	155	33.1
M[h]		Kiln	Spray tower/high-energy venturi/cyclone mist eliminator	1987	Monsanto[i]	7,470	264,000	67	152	33.1
N	Stauffer, Mont.	Kiln No. 1	Spray tower/wet ESP	1979	EPA[j]	NA	NA	NA	NA	NA
O		Kiln No. 1	None	1983	EPA[k]	2,240	79,200	350	660	15.8
P		Kiln No. 1	Spray tower only	1983	EPA[k]	681	24,100	15	59	2.1
Q		Kiln No. 1	Spray tower/wet ESP	1983	EPA[k]	614	21,700	13	55	1.7
R[l]	Occidental, Tenn.	Kiln No. 4	Low-energy scrubber	1985	Occidental[m]	3,250	115,000	73	163	18.8
S	FMC, Idaho	Calciner 1	None	1988	EPA[n]	8,760	309,000	240	460	11.0
T	FMC, Idaho	Calciner 1	Low-energy venturi/horizontal chevron-balde mist eliminator (typical ΔP)	1988	EPA[n]	7,390	261,000	59	138	19.1
U	FMC, Idaho	Calciner 1	Low-energy venturi/horizontal chevron-blade mist eliminator (maximum ΔP)	1988	EPA[n]	6,170	218,000	58	137	19.0
V	Monsanto, Idaho	Kiln	Spray tower	1988	EPA[o]	5,860	207,000	NA	NA	41.3
W	Monsanto, Idaho	Kiln	Spray tower/high-energy venturi/cyclone mist eliminator	1988	EPA[o]	5,760	203,000	NA	NA	38.9

[a] All tests are based on three-run averages unless noted otherwise.

[b] Each of the tests at FMC is from one of two parallel streams associated with one calciner (e.g., Calciner 2-1 is for test on Scrubber No. 1, Calciner No. 2.)

[c] References 6 and 12.

[d] Reference 13.

[e] Only dry standard conditions presented in test report.

[f] References 14 and 15.

[g] References 7 and 16.

[h] Based on 12 runs, 3 each on outlets of parallel scrubbing system.

[i] References 17 and 18.

[j] Reference 3.

[k] References 8 and 19.

[l] Two runs.

[m] Reference 20.

[n] Reference 21.

[o] Reference 22.

TABLE 3-4. CALCINER PM EMISSION DATA

Test ID[a]	Control measure[b]	Concentration		Emission rate	
		g/dscm	gr/dscf	kg/h	lb/h
A	None	1.0	0.45	98.4	217
B	None	6.9	3.0	835	1,840
C	SS/Cyc	0.089	0.039	12.0	26.4
D	SS/Cyc	0.32	0.14	35.9	79.1
E	SS/Cyc	0.14	0.063	13.7	30.3
F	SS/Cyc	NA	NA	8.44	18.6
G	SS/Cyc	NA	NA	8.84	19.5
H	SS/Cyc	0.046	0.020	5.31	11.7
I	SS/Cyc	0.062	0.027	9.44	20.8
J	LEV/Ch	0.032	0.014	4.72	10.4
K	LEV/Ch	0.018	0.008	2.77	6.1
L	ST	0.34	0.15	77.6	171
M	ST/HEV/Cyc	0.023	0.010	4.72	10.4
O	None	4.4	1.9	184	406
P	ST	0.14	0.060	4.54	10.0
Q	ST/WESP	0.060	0.026	1.81	4.0
R	LES	0.27	0.12	49.0	108
S	None	1.09	0.48	246	541
T	LEV/Ch	0.082	0.036	21.9	48.3
U	LEV/Ch	0.095	0.041	20.8	45.8
V	ST	0.59	0.26	104	230
W	ST/HEV/Cyc	0.027	0.012	4.90	10.8

[a] See references on Table 3-3.

[b] SS/Cyc = slinger scrubber with cyclone mist eliminator.
LEV = low-energy venturi.
HEV = high-energy venturi.
ST = spray tower
Ch = Chevron-blade mist eliminator.
LES = low-energy scrubber.
WESP = wet electrostatic precipitator.

TABLE 3-5. CALCINER RADIONUCLIDE EMISSION DATA

Test ID[a]	Control measure[b]	Po-210 emissions			Pb-210 emissions		
		pCi/g PM	nCi/dscm	Ci/yr	pCi/g PM	nCi/dscm	Ci/yr
A	None	4,100	4.6	3.3[c]	39	0.04	0.029[c]
B	None	1,050	6.2	6.1[c]	28	0.19	0.18[c]
C	SS/Cyc	17,000	1.44	1.4[c]	330	0.03	0.026[c]
D	SS/Cyc	12,000	3.04	2.6[c]	74	0.02	0.016[c]
E	SS/Cyc	27,000	3.80	2.7[c]	330	0.05	0.039[c]
F	SS/Cyc	25,000	1.47	1.2[d]			
G	SS/Cyc	29,000	1.43	1.7[d]			
H	SS/Cyc	21,000	0.961	0.72[d]			
I	SS/Cyc	18,000	1.10	1.36[d]			
J	LEV/Ch	37,000	1.18	1.24[d]			
K	LEV/Ch	38,000	1.96	2.04[d]			
L	ST	37,000	12.5	21[c]	9,700	3.3	5.6[c]
M	ST/HEV/Cyc	10,000	0.23	0.35[d]			
N	ST/WESP		0.23			0.34	
O	None				2,900	12.5	4.0[c]
P	ST	37,000	4.88	1.2[c]	4,800	0.65	0.16[c]
Q	ST/WESP	31,000	1.61	0.37[c]	4,600	0.25	0.056[c]
R	LES	850	0.23	0.36[d]	180	0.049	0.075[d]
S	None	4,400	4.8	8.0[c]	180	0.20	0.32[c]
T	LEV/Ch	55,000	4.5	9.0[c]	200	0.015	0.030[c]
U	LEV/Ch	51,000	4.9	7.9[c]	1,300	0.12	0.19[c]
V	ST	39,000	23	30[c]	2,200	7.3	9.5[c]
W	ST/HEV/Cyc	35,000	0.95	1.4[e]	8,200	0.23	0.34[e]

[a] See references on Table 3-3.

[b] SS/Cyc = slinger scrubber with cyclone mist eliminator.
LEV = low-energy venturi.
HEV = high-energy venturi.
ST = spray tower
Ch = Chevron-blade mist eliminator.
LES = low-energy scrubber.
WESP = wet electrostatic precipitator.

[c] Assumes plant operates 85 percent of time.

[d] Based on facility assumptions on operating rates.

[e] Assumes plant operates 95 percent of time.

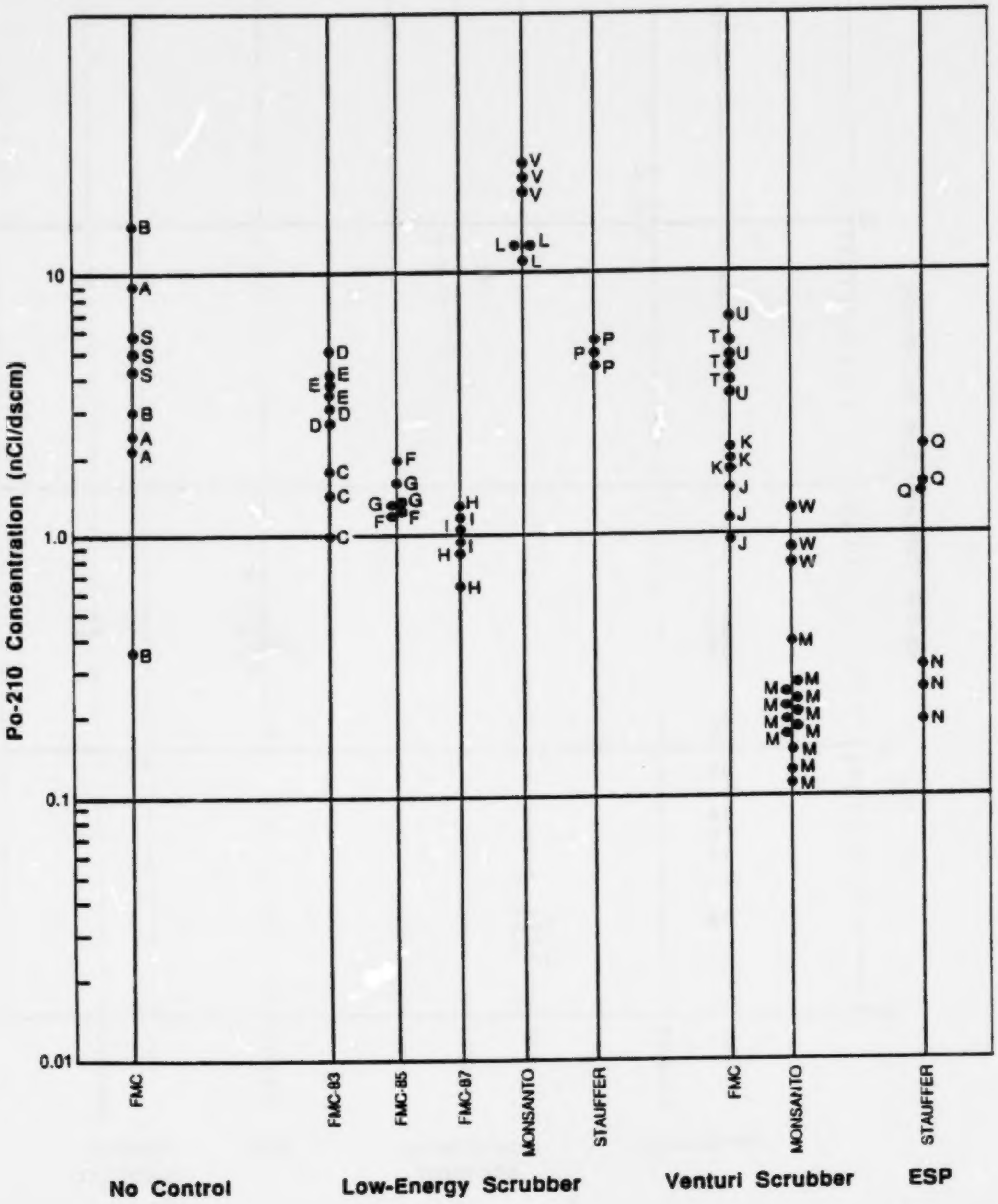

Figure 3-2. Summary of Po-210 emission data.

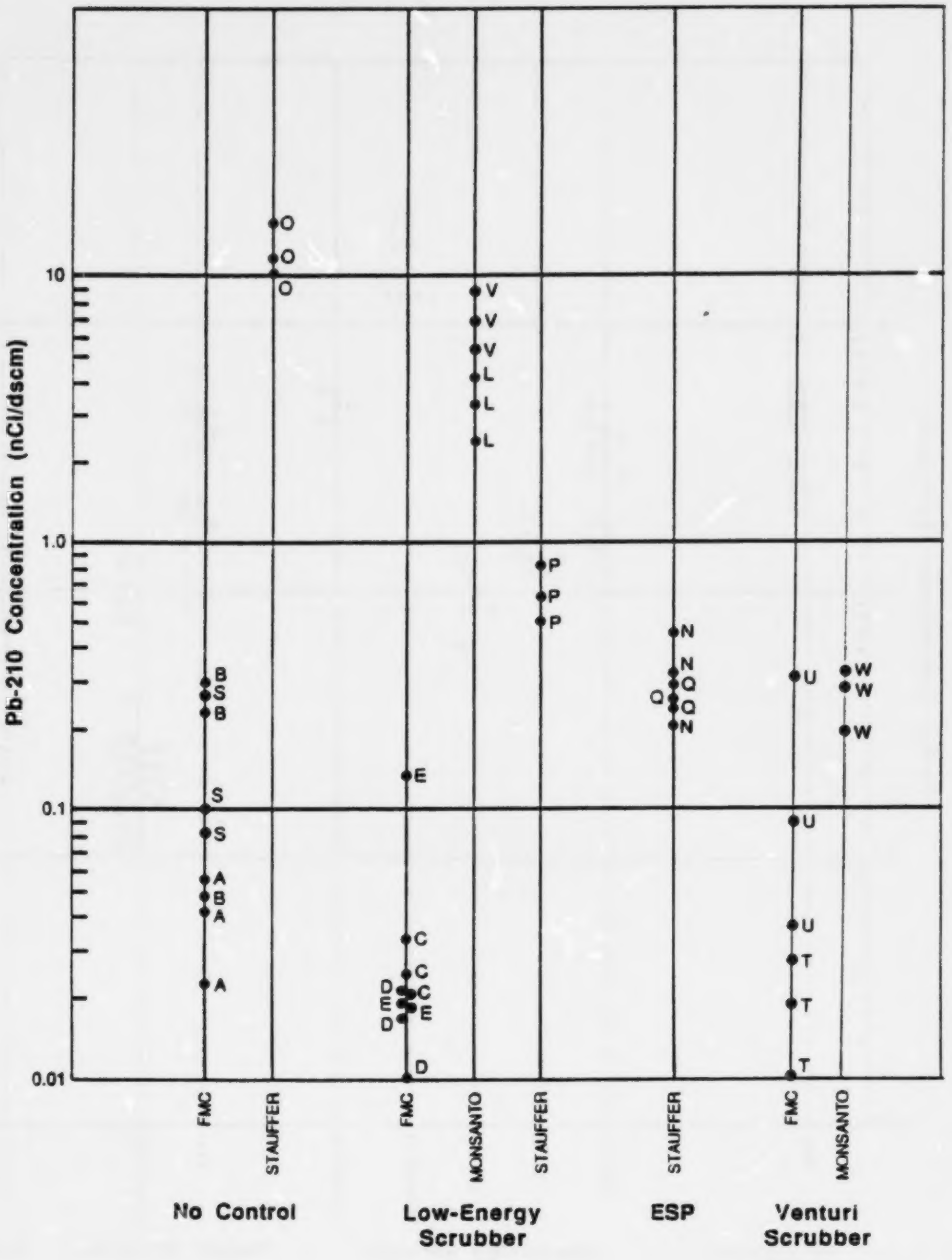

Figure 3-3. Summary of Pb-210 emission data.

wet ESP. The emission data presented in Table 3-5 and Figures 3-2 and 3-3 were not subjected to rigorous statistical analyses, but the graphical displays in Figures 3-2 and 3-3 provide substantive information on the Po-210 and Pb-210 emissions from different facilities with different control systems. The paragraphs below discuss the overall variability of the Po-210 and Pb-210 concentrations, with particular emphasis on the variability of emissions over time, and identify data that can be used to assess control device performance and the effects of new control systems on Po-210 and Pb-210 emissions.

The data presented in Figures 3-2 and 3-3 indicate that measured emissions for individual test runs range over almost 3 orders of magnitude for both Po-210 (approximately 0.1 to 30 nCi/dscm) and Pb-210 (less than 0.01 to 9 nCi/dscm). Contributors to this variability include the inherent imprecision in the sampling and analysis method, changes in operating conditions at a plant over time, plant to plant differences in ore feed characteristics and calciner operating conditions, and different levels of add-on air pollution control. The data collected to date are not sufficient to quantify the contributions of these different mechanisms to the overall variability in emissions. However, careful examination of the data in Figures 3-2 and 3-3 leads to the following qualitative observations.

1. The run-to-run variation within a given test sequence is relatively small. Generally the largest measured concentration for a given test is less than two to three times the smallest measured concentration. For Po-210, the two exceptions are Test A which ranges from about 2 nCi/dscm to 9 nCi/dscm (a factor of 4.5) and Test B which ranges from 0.4 to 16 nCi/dscm (a factor of 40). For Pb-210, primary exceptions are Test B which ranges from 0.04 to 0.3 nCi/dscm (a factor of 7.5), Test E which ranges from 0.02 to 0.12 nCi/dscm (a factor of 6), and Test U which ranges from 0.04 to 0.3 nCi/dscm (a factor of 7.5). Each of these tests was conducted on one of the two moving grate calciners. On balance, these data suggest that variation associated with sampling and analysis imprecision is reasonable, i.e., the variability in a 3-run test that is attributable to sampling and analysis imprecision is likely to be a factor of 3 or less. The data also suggest that emissions from moving grate calciners are more variable than those from kilns.

2. The test-to-test variability at the same plants at different times generally is greater than the within test run-to-run variability at those same facilities. Four sets of Po-210 test data illustrate this observation. Tests L and V were conducted at the outlet of the Monsanto spray tower in 1983 and 1988, respectively. The within test range was spanned by a factor of less than 1.5 for both tests while average emissions for the two tests were 12.5 nCi/dscm and 23 nCi/dscm, a factor of about 2. Tests at the outlet of the low-energy venturi scrubber at FMC were conducted in 1987 (Tests J and K) and 1988 (Test T). The within test run-to-run range spanned a factor of 2 or less for all three tests. However, average the emission concentration in 1987 was about 1.6 nCi/dscm and the average in 1988 was about 4.5 nCi/dscm, a factor of about 3. Tests were conducted at the outlet of the high energy venturi scrubber in 1987 (Test M) and 1988 (Test W). The 12 measurements in 1987 ranged over a factor of about 4 while the 3 measurements in 1988 ranged over a factor of about 1.5. In contrast, the average emissions in 1987 were 0.23 nCi/dscm while those in 1985 were 0.95 nCi/dscm, a factor of over 4. Because the individual test runs in 1985 represent different scrubbers, the range is larger than would be found for test runs on a single scrubber. Hence, the between test range is slightly larger than the within test range. Finally, tests were conducted at the outlet of the ESP at Stauffer in 1979 (Test N) and 1983 (Test Q). Within test run-to-run variability range over a factor of less than 2 for each test while average concentrations for the two tests were 0.23 nCi/dscm (1979) and 1.61 nCi/dscm (1983), a factor of between 7 and 8. These data, in combination with those presented in (1) above, suggest that the contribution of operating variability to overall variability in emission measurements is somewhat greater than the contribution of sampling and analysis imprecision.

3. Control systems comprising a spray tower and high energy venturi or a spray tower and wet ESP can achieve significant reductions (greater than 90 percent) in Po-210 and Pb-210 emissions. This observation is based on comparison of the tests at the outlet to the Monsanto spray tower (Tests L and V) to the emissions at the venturi outlet (Tests M and W) and the tests at the spray tower inlet (Test O), spray tower outlet (Test P)

and ESP outlet (Tests Q and N) at Stauffer. The performance of these control systems is analyzed in more detail in Section 4.

3.2.2 Acid Gas Emissions

Elemental phosphorus calcining operations are sources of acid gas emissions that can include SO_2, HF, HCl, and P_2O_5. However, the primary constituents are SO_2 and HF. These acids are generated by fluorides and sulfides that are contained in the phosphate ores and in coal that is used to supplement the CO as fuel in the calciner. This study is not concerned directly with acid gas emissions, but they do play an important role in evaluating emission control alternatives. Consequently, available data were collected from emission test reports, and information on acid gas levels was requested from plant personnel during plant visits. The limited data that were obtained are presented in Table 3-6.

3.2.3 Po-210 and Pb-210 Particle Size Distributions

The control technology assessments in Chapter 4 require an estimate of the particle size distributions of Po-210 and Pb-210 emissions. The only radionuclide-specific particle size data that were identified during this study were those generated by EPA in support of NESHAP development. During that comprehensive test program, particle size data were collected at the inlets and outlets of control systems at the three Western plants using one of two methods--a cascade impactor or the SASS cyclones. The data generated from that program are tabulated in Tables 3-7 and 3-8 for the impactor samples and SASS samples, respectively.

The data in Table 3-7 indicate the distributions at the scrubber inlet are distinctly different from those at the outlet at FMC. In general, the inlet data are bimodal with significant fractions of the emissions less than 1.0 μm and greater than 10 μm in diameter. At the outlet, over 70 percent of the Po-210 and Pb-210 were in the two fractions that were less than 0.9 μm in diameter except for the Pb-210 on Calciner No. 1 at FMC. Consequently, additional controls must focus on submicron PM.

The data in Table 3-7 also indicate that the distributions of both Po-210 and Pb-210 at Stauffer and Monsanto are different from those at FMC. However, the SASS results in Table 3-8 and the cascade impactor tests in Table 3-7 indicate that the distributions at Monsanto are

TABLE 3-6. ACID GAS EMISSION LEVELS

Facility	Location	HF levels		SO_2 levels		Ref.
		ppmv	kg/h	ppmv	kg/h	
FMC, Idaho	Stack	18-40	6-8	200		14,15
Monsanto, Idaho	Stack		1.5			17
Stauffer, Mont.	Kiln exhaust		45		68	3
Stauffer, Tenn.	Kiln exhaust		180		250	21
	Stack		0.7		64	21
Occidental, Tenn.	Stack	66		774		20

TABLE 3-7. PARTICLE SIZE DISTRIBUTION BASED ON IMPACTOR SAMPLES

Pollutant	Control level	Facility/ location	Percentage of pollutant in size range					
			Approximate particle size D-50, µm					
			<0.5	0.5–0.9	0.9–1.5	1.5–3	3–10	>10
Po-210	None	FMC/2-1	33.5	3.9	4.9	5.8	18.0	33.9
		FMC/2-2	23.8	2.6	3.8	5.2	15.6	49.0
		FMC/1	65.0	7.5	6.0	6.9	7.6	7.0
	Low-energy scrubber	FMC/2-2	70.7	6.1	7.5	5.6	6.8	3.3
		FMC/1-1	71.6	3.1	1.6	1.3	1.9	20.4
		FMC/1-2	85.8	2.9	2.3	1.4	2.5	5.1
		Stauffer	52.2	21.6	12.9	8.9	3.4	1.0
		Monsanto	60.0	26.5	6.8	4.7	1.4	0.6
	ESP	Stauffer	50.1	23.5	16.5	4.4	3.5	2.0
	Venturi	Monsanto	70.0	18.0	5.3	4.7	1.4	0.6
		FMC/1	72.5	7.8	5.7	5.5	5.8	2.7
Pb-210	None	FMC/2-1	41.5	6.2	9.5	11.8	13.0	18.0
		FMC/2-2	12.4	2.4	1.8	1.3	32.3	49.7
		FMC/1	30.0	12.5	13.3	12.2	19.0	13.0
	Low-energy scrubber	FMC/2-2	61.2	11.8	4.6	8.8	9.5	4.0
		FMC/1-1	26.9	17.9	21.4	4.8	13.1	15.8
		FMC/1-2	21.3	23.4	8.5	12.8	17.0	17.0
		Stauffer	60.0	18.1	14.3	5.2	2.0	0.4
		Monsanto	60.0	26.5	7.5	4.0	1.8	0.2
	ESP	Stauffer	54.1	22.4	14.1	4.9	3.3	1.2
	Venturi	Monsanto	60.0	26.5	8.5	3.5	1.2	0.3
		FMC/1	53.5	14.5	11.0	10.5	8.2	2.3

TABLE 3-8. PARTICLE SIZE DATA BASED ON SASS CYCLONE SAMPLES

			Percentage of pollutant in size range			
			Approximate particle size D-50, μm			
Pollutant	Facility	Location	<1	1-3	3-10	>10
Po-210	Stauffer	Spray tower outlet	72.2	9.6	0.4	17.8
		ESP outlet	91.2	0.3	0.1	8.4
	Monsanto	Stack	94.6	3.7	0.5	1.2
Pb-210	Stauffer	Spray tower outlet	92.4	4.0	0.2	3.4
		ESP outlet	96.9	1.1	0.1	1.9
	Monsanto	Stack	93.7	4.3	0.6	1.4

comparable to those at Stauffer. In the absence of other information, these data suggest that distinct particle size distributions should be used for moving grate calciners (FMC) and nodulizing kilns (all other plants) in the control technology assessments. The data from the earlier tests indicate that the cascade impactor data from Stauffer and the Monsanto values from 1988 are the most reliable data for kiln particle size estimates. The cascade impactor data from FMC are the only data available for the moving grate calciner.

3.3 KILN BASELINE EMISSIONS

Baseline estimates of the annual emissions of Po-210 and Pb-210 from each of the five operating facilities were developed on the basis of actual emissions at the control device outlet and regulatory emission levels. Actual baseline emission estimates are based on the most recent emission tests conducted by either the facility or EPA. Regulatory baseline emission estimates were based on the PM emission limits imposed by the States and best estimates of radionuclide activity levels in PM emissions. The results of these analyses are presented in Table 3-9.

TABLE 3-9. BASELINE Po-210 AND Pb-210 EMISSIONS

Facility	Actual emissions, Ci/yr		PM emission limit, lb/h[7]	Regulatory baseline, Ci/yr	
	Po-210	Pb-210		Po-210	Pb-210
FMC-Idaho[a]	10.0[b]	0.14[c]	304	57	0.29
Monsanto-Idaho[c]	1.4[d]	0.34[d]	33	4.9	1.3
Stauffer-Mont[e]	0.74[f]	0.11[f]	58[g]	6.0	0.89
Stauffer-Tenn.[h]	0.28[i]	0.058[i]	78.4	0.26	0.0056
Occidental-Tenn.[h]	0.31[j]	0.064[j]	437	1.5	0.31

[a] Based on facility production data.

[b] Based on EPA tests of 1983 and 1988.

[c] Assumes 90 percent operation.

[d] Based on EPA 1988 tests.

[e] Assumes kiln operates 85 percent of time.

[f] Based on EPA 1983 tests.

[g] Based on twice Montana limit for No. 2 kiln.

[h] Estimated based on data supplied by facilities. Operating rate estimated to be in the range of 85 to 100 percent of capacity.

[i] Estimated based on Occidental emissions and relative plant capacities.

[j] Based on plant tests conducted in 1985.

3.4 REFERENCES FOR SECTION 3

1. Eadie, G. and Bernhardt, D. Radiological Survey of Idaho Ore Processing--The Thermal Process Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada. Technical Note, ORP/LV-77-3. November 1977.

2. Andrews, V. Emissions of Naturally Occurring Radioactivity from Monsanto Elemental Phosphorus Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada. Publication No. EPA-520/6-82-021. November 1982.

3. Andrews, V. Emissions of Naturally Occurring Radioactivity from Stauffer Elemental Phosphorus Plant. Prepared for U. S. Environmental Protection Agency. Las Vegas, Nevada. Publication No. EPA-520/6-82-019. November 1982.

4. Weast, R. C., ed. CRC Handbook of Chemistry and Physics, 64th Edition. Cleveland. The Chemical Rubber Company. 1984. p. D-196.

5. Brooks, L. S. The Vapor Pressure of Polonium. Journal of the American Chemical Society. 77:3211. 1955.

6. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: FMC Plant, Pocatello, Idaho. Washington, D.C. June 1984.

7. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: Monsanto Plant, Soda Springs, Idaho. Washington, D.C. September 1984.

8. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: Stauffer Plant, Silver Bow, Montana. Washington, D.C. U. S. EPA. August 1984.

9. Stula, R. T., R. E. Balanger, C. L. Clary, R. F. May, M. E. Spaeth, and J. P. Swenson. Airborne Emission Control Technology for the Elemental Phosphorus Industry, Final Report for EPA Contract No. 68-01-6429. Science Applications, Inc. La Jolla, California. January 1984.

10. Memo and attachments from Leeds, K., Midwest Research Institute, to Beck, L., EPA/ISB. October 14, 1988. State Emissions Standards for Elemental Phosphorus Plants.

11. Cowherd, C., G. Muleski, and J. Kinsey. Control of Open Fugitive Dust Sources. Prepared for U. S. Environmental Protection Agency. Research Triangle Park, North Carolina. Publication No. EPA-450/3-88-008. September 1988.

12. Radian Corporation. Emission Testing of Calciner Off-Gases At FMC Elemental Phosphorus Plant, Pocatello, Idaho. Emission Test Final Report, Volume I. Prepared for U. S. Environmental Protection Agency under Contract No. 68-07-3174. Research Triangle Park, North Carolina. August 1984.

13. Letter from Hebert, F., FMC, to O'Neal, G., EPA. September 6, 1985. Summary of 1985 emission test results.

14. Letter from Bowman, M., FMC Corporation, to Magno, P., EPA/ORP. February 26, 1988. Summary of FMC emission data.

15. Memo and attachments from Wallace D., and K. Leeds, Midwest Research Institute, to Beck, L., EPA/ISB. August 9, 1988. Site Visit--FMC Corporation, Pocatello, Idaho.

16. Radian Corporation. Emission Testing of Calciner Off-gases at Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho. Emission Test Final Report, Vol. I. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-3174. Research Triangle Park, North Carolina. August 1984.

17. Memo and attachments from Wallace, D., and K. Leeds, Midwest Research Institute to Beck, L., EPA/ISB. August 9, 1988. Site Visit--Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho.

18. Letter from Wind, D., Monsanto Chemical Company, to McLaughlin, T., EPA/ORP. May 10, 1988. Emission data from Monsanto, Soda Springs, facility.

19. Radian Corporation. Emission Testing of Calciner Off-Gases At Stauffer Chemical Elemental Phosphorus Plant, Silver Bow, Montana. Emission Test Final Report, Volume I. Prepared for U. S. Environmental Protection Agency under Contract No. 68-07-3174. Research Triangle Park, North Carolina. August 1984.

20. Memo and attachments from Wallace, D., and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 23, 1988. Site Visit--Occidental Elemental Phosphorus Plant, Columbia, Tennessee.

21. Radian Corporation. Draft Final Emission Test Report, FMC Elemental Phosphorus Plant, Pocatello, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

22. Radian Corporation. Draft Final Emission Test Report, Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

23. Memo and attachments from Wallace, D., and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 23, 1988. Site Visit--Stauffer Elemental Phosphorus Plant, Mount Pleasant, Tennessee.

4. EMISSION CONTROLS

The nodulizing kiln or calciner is by far the most significant source of P -210 and Pb-210 emissions from elemental phosphorus production. This sect on describes and assesses control technologies that can be used to red e those emissions. Generally Po-210 and Pb-210 are volatilized in the iln or calciner and preferentially condense on the fine particles in the alciner PM emission stream. The control systems that are installed in t e industry effectively collect large particles, but they are not eff tive controlling fine particle emissions. Consequently, the technologi examined in this section are those that have been demonstrated to ach ve high control efficiencies on fine particles. However, control of Po- 0 and Pb-210 emissions is complicated by two factors. First, because the emperature of the flue gas leaving the kiln may be 400°C (750°F) or hig r, significant concentrations of Po-210 can remain in the vapor phase (see Figure 3-1). Second, the exhaust contains relatively high concentratio of SO_2 and HF; these acid gases can condense in the control system lea ng to subsequent corrosion and deterioration of performance. Mec nisms for cooling the exhaust gases and reducing the acid gas concentrat on in the gases are discussed later in this section.

Applicable control systems for the kiln or calciner emissions are exa ned in the three subsections below. The first describes the control syst ms; discusses the operating principles of each system; and identifies key sign and operating parameters which affect performance, as measured by P -210 and Pb-210 reduction, and costs. The second describes procedure for estimating the performance of each type of control system and disc sses the emission data that are available on system performance. The thir describes the general procedures for estimating the costs for each cont l system and presents assumptions used to develop estimates for majo cost elements for each of the control systems. Details of specific cont l alternatives and the performance and cost of those alternatives are ntained in Section 5.

4.1 DESCRIPTION OF APPLICABLE CONTROL SYSTEMS

The four fine PM control techniques examined during this study are wet electrostatic precipitators (wet ESP's), venturi scrubbers, spray dryers with pulse jet fabric filters (SD/FF's), and high-efficiency particulate air (HEPA) filters. The wet ESP and venturi scrubber were selected because they are the control systems that are used at operating elemental phosphorus plants. The SD/FF and HEPA were selected as high-efficiency PM control devices that have excellent potential for controlling Po-210 and Pb-210 emissions but that have not been applied to elemental phosphorus plants. The SD/FF systems have been applied successfully to combustion sources and mineral and metallurgical furnaces and have demonstrated high control efficiencies for condensible metals and acid gases. The HEPA filter has been demonstrated to achieve high control efficiencies on radionuclide emissions from uranium industry processes.

Four of the five operating elemental phosphorus facilities currently operate spray towers as either the primary control system or as a gas conditioning technique. These spray towers will remove coarse PM as well as acid gases from the gas stream. All of the control techniques, except the SD/FF, can benefit from inclusion of a spray tower upstream of the primary fine PM control device to reduce temperature, gas volume, and acid gas concentration.

The five subsections below address spray towers and the four fine PM control techniques individually. Each section includes a description of the control technique, a discussion of the operating principles for the technique, and identification of the key design and operating parameters.

4.1.1 Spray Towers

A spray tower is one of the most simply constructed wet scrubbers, comprising a cylindrical vessel constructed of steel, plastic, or wood and one or more sets of nozzles that are used to spray liquid into the gas stream. The exhaust gas generally enters the bottom of the tower and moves upward as shown in Figure 4-1.[1] Liquid, generally water or a slurry of water and lime, is sprayed downward from one or more levels to provide a countercurrent flow of liquid and gas in the tower. This countercurrent flow exposes the exhaust gas with lowest pollutant concentration to the freshest scrubbing liquor.

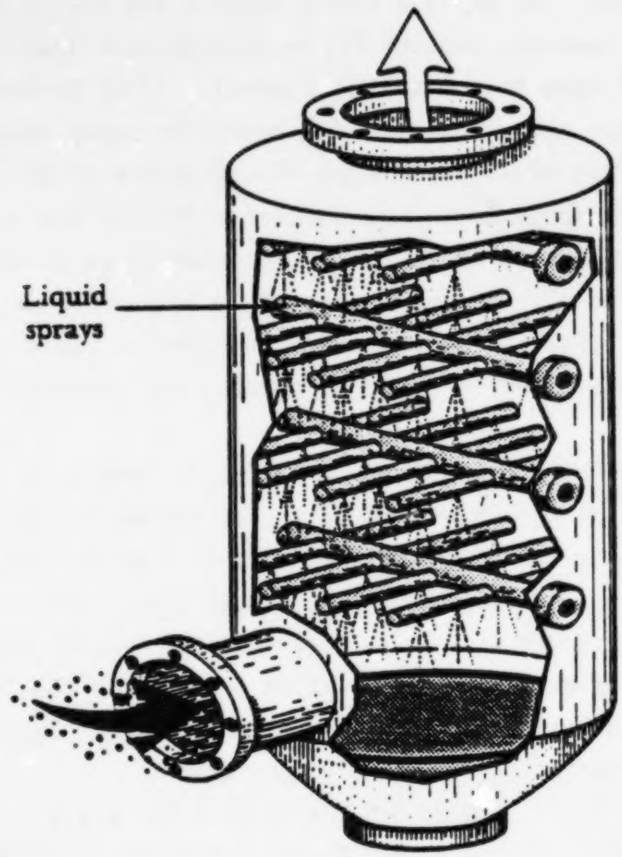
Liquid
sprays

Figure 4-1. Countercurrent flow spray tower.[1]

As a preconditioner upstream from a fine PM control device, a spray tower serves three functions. First, it reduces the temperature of the gas stream by evaporative cooling. This temperature reduction enhances Po-210 and Pb-210 control by increasing condensation, and it reduces the gas volume that must be treated by the fine PM control system. Second, the spray tower reduces the concentration of SO_2 and HF in the control stream by absorption. The HF is a highly soluble gas and is absorbed readily in water. However, because SO_2 is less soluble than HF, a lime slurry typically is used to enhance SO_2 removal. Plant personnel contacted during this study indicate that operating spray towers generally achieve SO_2 reductions of 75 percent and HF reductions of 99 percent or more.[2,3] Third, the spray tower removes coarse PM from the gas stream. Typical efficiencies for spray towers are reported to be 90 percent on particles 5 μm in diameter or greater and 60 to 80 percent on particles in the 3 to 5 μm size range.[4] The test data presented in Table 3-4 indicate that a PM control efficiency of about 97 percent was achieved by the spray tower at Stauffer.

The primary PM collection mechanism for spray towers is inertial impaction of particles to liquid droplets. Key parameters that affect particle collection by impaction for particles of a given size are scrubbing zone height, gas velocity in the spray tower (generally pressure drop (ΔP) across the tower is used as a surrogate), liquid-to-gas (L/G) ratio, and spray droplet size. The pressure drop across the tower and the L/G ratios affect operating cost as well as performance. Typical values of operating characteristics for spray towers are:

ΔP[5]	0.25-0.5 kPa (1 to 4 in. w.c.)
L/G ratio[5]	1.3 to 2.7 ℓ/m^3 (10 to 20 gal/kacfm)
Droplet size[1]	500 to 1,000 μm

The primary acid gas collection mechanism in spray towers is absorption. Removal of a gaseous pollutant by absorption requires intimate contact between the exhaust stream and the sorbent liquid. Three steps are involved in absorption. In the first step, the gaseous pollutant diffuses from the bulk area of the gas phase to the gas-liquid interface. In the second step, the gas moves (transfers) across the interface to the liquid phase. This step is extremely rapid once the gas molecules (pollutant) arrive at the interface area. In the third step, the gas diffuses into the bulk area of the liquid, thus making room for additional gas molecules to be absorbed. The rate of absorption (mass transfer of the pollutant from the gas phase to the liquid phase) depends on the diffusion rates of the pollutant in the gas phase (first step) and in the liquid phase (third step). For HF, which is highly soluble, the rate is gas-phase controlled. For the less soluble SO_2, the rate is liquid-phase controlled and depends on the reaction rate of SO_2 with lime to form calcium sulfate.

The following design factors enhance gas diffusion, and, therefore, absorption:

1. Large interfacial contact area between the gas and liquid phases;
2. Good mixing of the gas and liquid phases (turbulence); and
3. Sufficient residence or contact time between the phases for absorption to occur.

An important factor affecting the amount of a pollutant that can be absorbed is its solubility. Solubility governs the amount of liquid (L/G ratio) required and the necessary contact time. More soluble gases (such as HF) require less liquid. Also, more soluble gases will be absorbed faster. Solubility is a function of temperature. As temperature increases, the amount of gas that can be absorbed by a liquid decreases. The solubility and gas scrubbing efficiency also are affected by the pH of the scrubbing liquor. Plant personnel indicate that for SO_2, efficiency increases monotonically with the pH of the scrubbing liquor (i.e., an increase of pH will increase scrubber efficiency). However, for HF, the optimal scrubbing efficiency is achieved at a pH of about 7.5 to 8.0, and higher pH levels result in significant decreases in efficiency. The pH in the spray towers at the elemental phosphorus plants in Tennessee generally is maintained in the range of 7.5 to 8.0.[3] Personnel at the western elemental phosphorus plants indicated that the characteristics of their PM and water necessitate maintenance of pH in the range of 4.5 to 5.0 to inhibit precipitation and scaling in the scrubbing system.[7]

4.1.2 Venturi Scrubbers

A venturi scrubber is a high-efficiency PM control device that enhances particle collection by generating high-velocity, turbulent flow conditions in the gas stream. A venturi scrubber consists of three sections--a converging section, a throat section, and a diverging section as shown in Figure 4-2.[1] The exhaust stream enters the converging section, and gas velocity and turbulence increase. Liquid is introduced either at the throat or at the entrance to the converging section. In the throat, the gas stream is mixed with the droplets that are sheared from the walls, and gaseous and particulate pollutants are transferred from the gas stream to these droplets. The exhaust stream then exits through the diverging section. Venturis can be used to collect both particulate and gaseous pollutants, but they are more effective in removing particles than in removing gaseous pollutants.

Liquid can be injected at the converging section or at the throat. Figure 4-3 shows liquid injected at the converging section. Because this type of venturi provides a liquid coat on the throat surface, it is very effective for handling hot, dry exhaust gases that contain dusts that tend to cake on or abrade a dry throat. Generally, this wet throat approach is more appropriate for application to elemental phosphorus kiln or calciner operations for two reasons. First, because the gas stream contains high concentrations of HF and SO_2, the wetting/drying phenomena that occurs at the throat in dry throat applications can result in increased corrosion. Second, the PM in these exhaust streams has a tendency to scale, and this scaling is enhanced in a dry throat. Consequently, the wetted throat has fewer operation and maintenance problems and achieves better long-term performance than the dry throat.

Manufacturers have developed modifications to the basic venturi design to maintain scrubber efficiency by changing the pressure drop for varying exhaust gas rates. One particular development is the annular-orifice, or adjustable-throat, venturi scrubber (Figure 4-4). The throat area is varied by moving a plunger, or adjustable disk, up or down in the throat, decreasing or increasing the annular opening. Gas flows through the annular opening and atomizes liquid that is sprayed onto the plunger or swirled in from the top. One of the two venturi scrubbers installed at

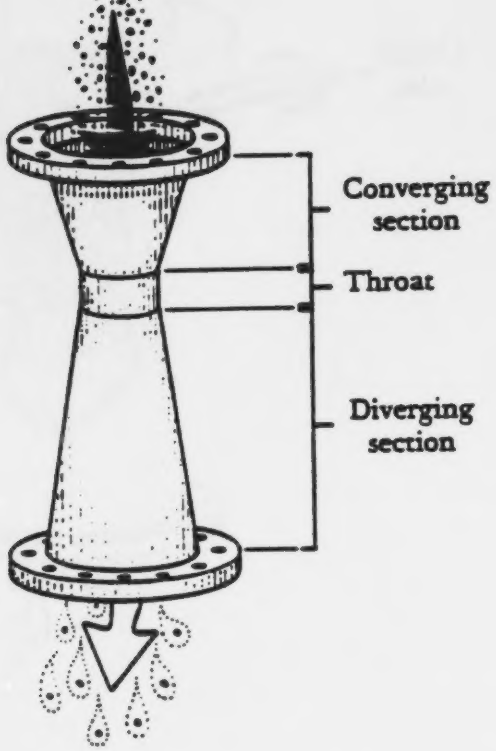
Converging section
Throat
Diverging section

Figure 4-2. Venturi scrubber.[1]

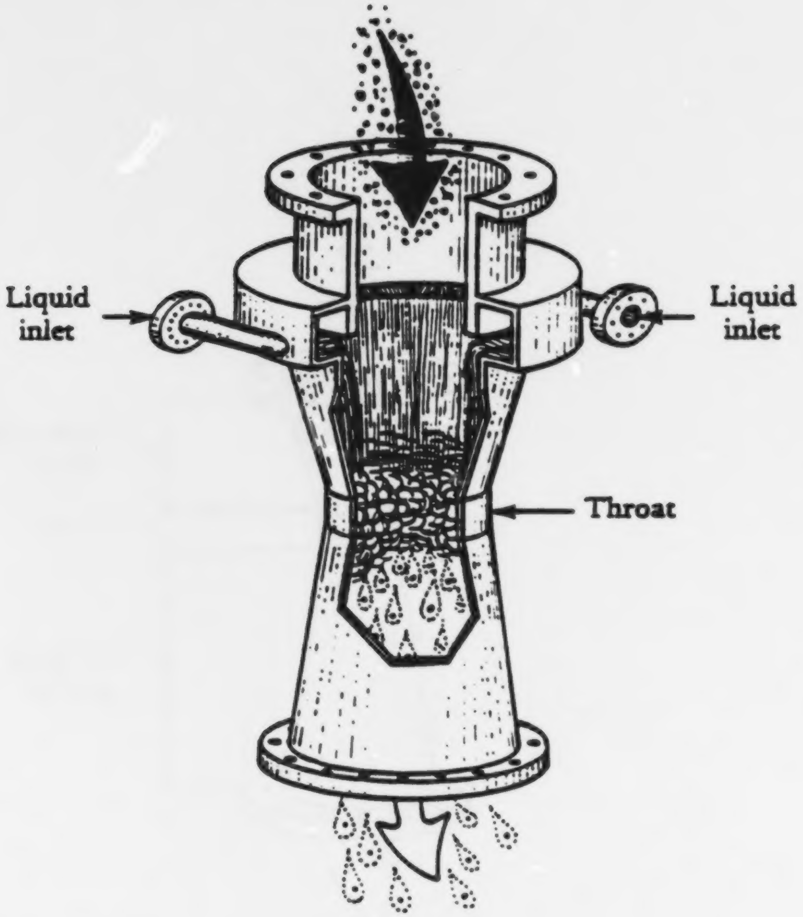
Liquid inlet
Liquid inlet
Throat

Figure 4-3. Wetted-throat venturi scrubber.[1].

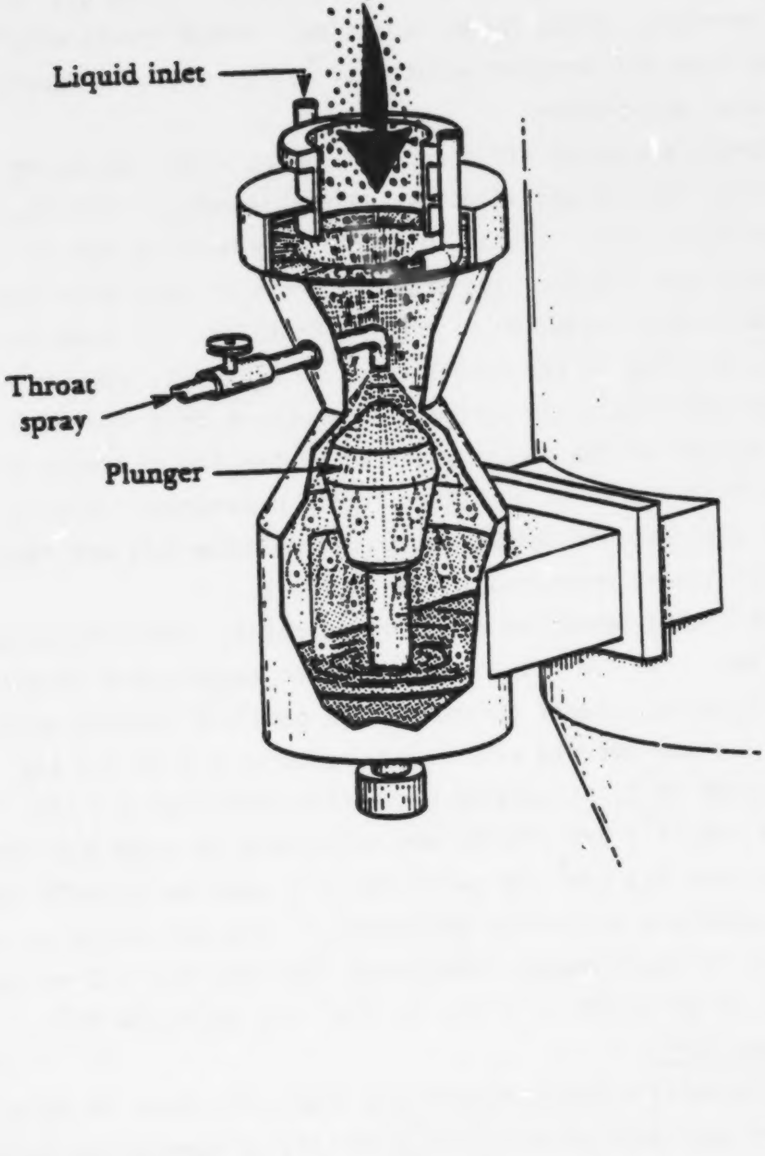
Liquid inlet
Throat spray
Plunger

Figure 4-4. Adjustable-throat venturi scrubber.[1]

elemental phosphorus plants is a movable throat venturi. The other is a fixed-throat, tandem-nozzle unit.

Venturis are the scrubbers used most commonly at elemental phosphorous plants and are capable of achieving the high particle collection efficiency. As the exhaust stream enters the throat, its velocity increases greatly, resulting in droplet atomization and turbulent mixing of the gas with any liquid present. Particulate matter in the gas is collected in these droplets, primarily by impaction. These liquid droplets then are removed from the scrubber exhaust stream by cyclonic separators or chevron-blade mist eliminators.

Particle removal efficiency increases with increasing pressure drop (resulting in high gas velocity and turbulence.) Venturis can be operated with pressure drops ranging from 1 to 25 kPa (5 to 100 in. w.c.). Venturi scrubbers that operate with pressure drops of less than 12.5 kPa (50 in. w.c.) have been installed on nodulizing kilns. At these pressure drops, the gas velocity in the throat section is usually between 30 and 120 m/s (100 and 400 ft/s). An increase in pressure drop increases operating costs because of the energy required by the fan to remove the large air volumes from the kilns at higher static pressures. It also increases capital cost because thicker construction materials are required to handle the lower static pressures in the ductwork.

The liquid injection rate, or L/G ratio, also affects particle collection. The L/G ratio depends on the temperature (evaporation losses) of the incoming exhaust stream and the particle concentration. Most venturi systems operate with an L/G ratio of 0.4 to 1.3 ℓ/m^3 (3 to 10 gal/1,000 ft^3). Liquid-to-gas ratios less than 0.4 ℓ/m^3 (3 gal/1,000 ft^3) are usually not sufficient to cover the throat, and adding more than 1.3 ℓ/m^3 (10 gal/1,000 ft^3) does not usually significantly improve particle collection efficiency.[1] The two operating venturi scrubbers in the elemental phosphorus industry have L/G ratios of about 0.8 ℓ/m^3 (6 gal/1,000 ft^3) and 2.4 ℓ/m^3 (18 gal/1,000 ft^3).

4.1.3 Wet ESP's

Electrostatic precipitators are high-efficiency PM collection devices that have been applied widely to a variety of combustion sources and metallurgical furnaces that have a wide range of combustion gas characteristics. Particle collection is accomplished by exposing the gas stream to a high-energy electrical field which charges particles and moves them to an oppositely charged surface (the collection electrode) where they are collected. The primary characteristic that distinguishes wet ESP's from dry ESP's is the use of liquid flow rather than rapping to remove the collected PM from the collection electrode. The discussion below addresses only wet ESP's.

The basic principles of the electrostatic precipitation process are (1) development of a high-voltage direct current that is used to charge particles in the gas stream, (2) development of an electric field in the space between the discharge electrode and the positively charged collection electrode that propels the negatively charged ions and particulate matter toward the collection electrode, and (3) removal of the collected particulate by use of water flushing. These basic principles of the electrostatic precipitation process are illustrated in Figure 4-5.

The electrostatic precipitation process occurs within an enclosed chamber; a high-voltage transformer (to step up the line voltage) and a rectifier (to convert AC voltage to DC) provide the power input. The precipitation chamber has a shell made of metal, tile, or fiberglass-reinforced plastic (FRP). Suspended within this shell are the grounded collecting electrodes (usually plates), which are connected to the grounded steel framework of the supporting structure and to an earth-driven ground. Suspended between the collection plates are the discharge electrodes, also known as corona electrodes, which are insulated from the ground and negatively charged with voltages ranging from 20 kV to 100 kV. The large difference in voltage between the negatively charged discharge electrode and positively charged collection electrode creates the electric field that drives the negatively charged ions and particles toward the collection electrode.

The last segment of the process covers the removal of the dust from the collection electrodes. In wet ESP's, the collected particulate matter is removed by an intermittent or continuous stream of water that flows down over the collection electrodes and into a receiving sump. The liquid from the sump is circulated through a treatment system to remove suspended particles and adjust pH.

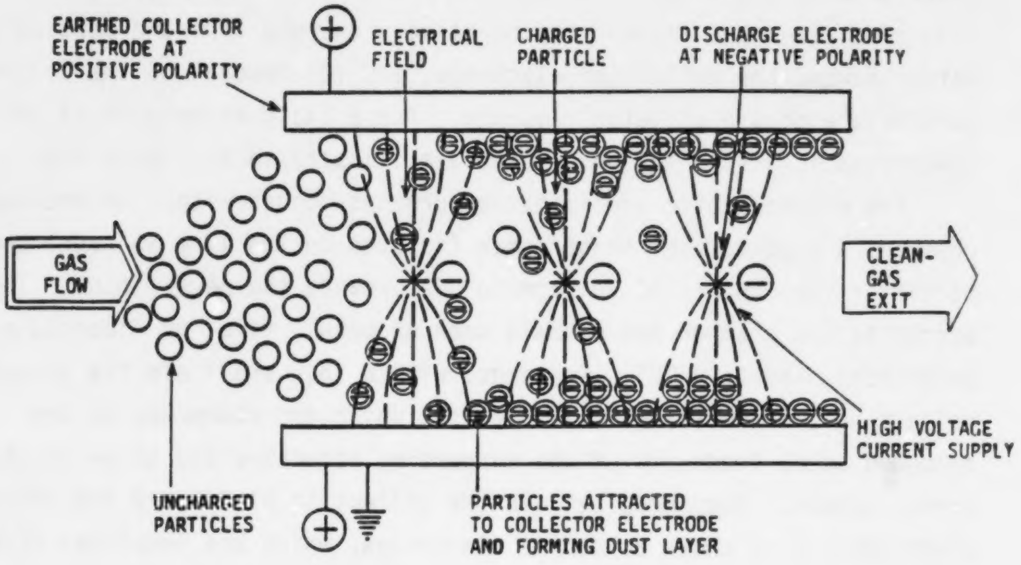
EARTHED COLLECTOR ELECTRODE AT POSITIVE POLARITY
+
ELECTRICAL FIELD
CHARGED PARTICLE
DISCHARGE ELECTRODE AT NEGATIVE POLARITY
GAS FLOW
CLEAN-GAS EXIT
HIGH VOLTAGE CURRENT SUPPLY
UNCHARGED PARTICLES
+
PARTICLES ATTRACTED TO COLLECTOR ELECTRODE AND FORMING DUST LAYER

Figure 4-5. Illustration of ESP operating principles.[8]

The major differences in the types of wet ESP's are the shape of the collector, whether treatment of the gas stream is vertical or horizontal, whether incoming gas is preconditioned with water sprays, and whether the entire ESP is operated wet. Figures 4-6 and 4-7 show two types of wet ESP's, the circular-plate variety and the square or rectangular flat-plate type. One wet ESP currently is installed on one nodulizing kiln. The ESP is a circular-plate type with a spray tower upstream of the ESP to condition the gas stream. Plant personnel indicated that when the ESP reaches the end of its useful life, they probably will install a flat-plate system because it is easier to maintain than the circular-plate unit.

The casing can be constructed of steel or FRP, and discharge electrodes can be carbon steel, special alloys, or FRP, depending on the corrosiveness of the gas stream. The system that presently is in use has FRP plates, but plant personnel indicated that these plates have not lasted well in the cold winter environment in Montana. However, because the kiln exhaust is corrosive and liquid pH must be maintained at 5 or less, the plates must be constructed of FRP or corrosion-resistant alloys.

In circular-plate wet ESP's, the circular plates are irrigated continuously; this continuous flow provides the electrical ground for attracting the particles and also removes them from the plate. These systems can generally handle flow rates of 850 to 2,800 m^3/min (30,000 to 100,000 ft^3/min). Preconditioning sprays remove a significant amount of particulate by impaction. Pressure drop through these units usually ranges from 0.25 to 0.75 kPa (1 to 3 in. w.c.).[8]

Rectangular flat-plate units operate in basically the same manner as the circular-plate wet ESP's. Water sprays in an inlet plenum or in an upstream spray tower precondition the incoming gas and provide some initial particulate removal. The water sprays are located over the top of the electrostatic fields, and collection plates are irrigated continuously. The collected particulate flows downward into a trough that is sloped to a drain. Typically the water is treated onsite to remove the suspended solids, and treated water is recycled to the system. Plant personnel indicated that the water for the ESP currently operating at an elemental phosphorous facility is treated to a pH of about 5 to prevent scaling on the plates.[7]

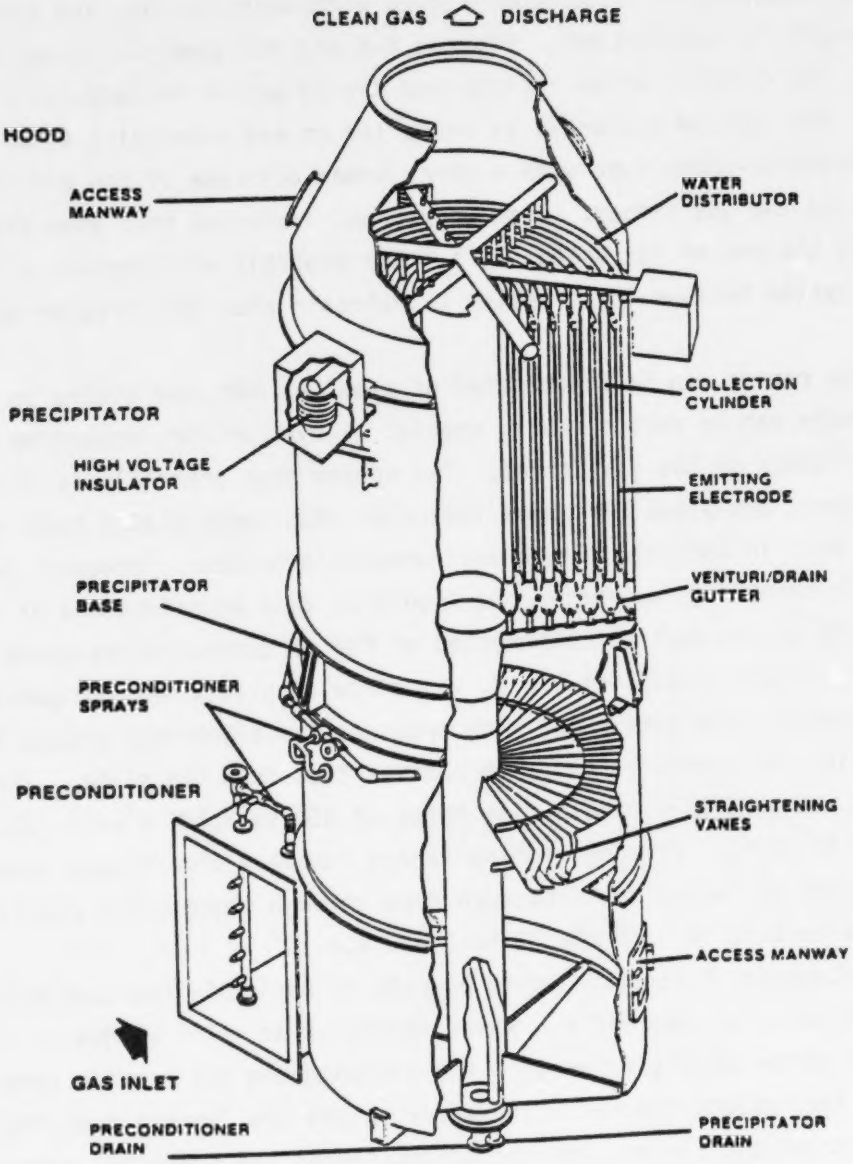
CLEAN GAS DISCHARGE
HOOD
ACCESS MANWAY
WATER DISTRIBUTOR
COLLECTION CYLINDER
PRECIPITATOR
HIGH VOLTAGE INSULATOR
EMITTING ELECTRODE
VENTURI/DRAIN GUTTER
PRECIPITATOR BASE
PRECONDITIONER SPRAYS
PRECONDITIONER
STRAIGHTENING VANES
ACCESS MANWAY
GAS INLET
PRECONDITIONER DRAIN
PRECIPITATOR DRAIN

Figure 4-6. Circular-plate type wet ESP.[8]

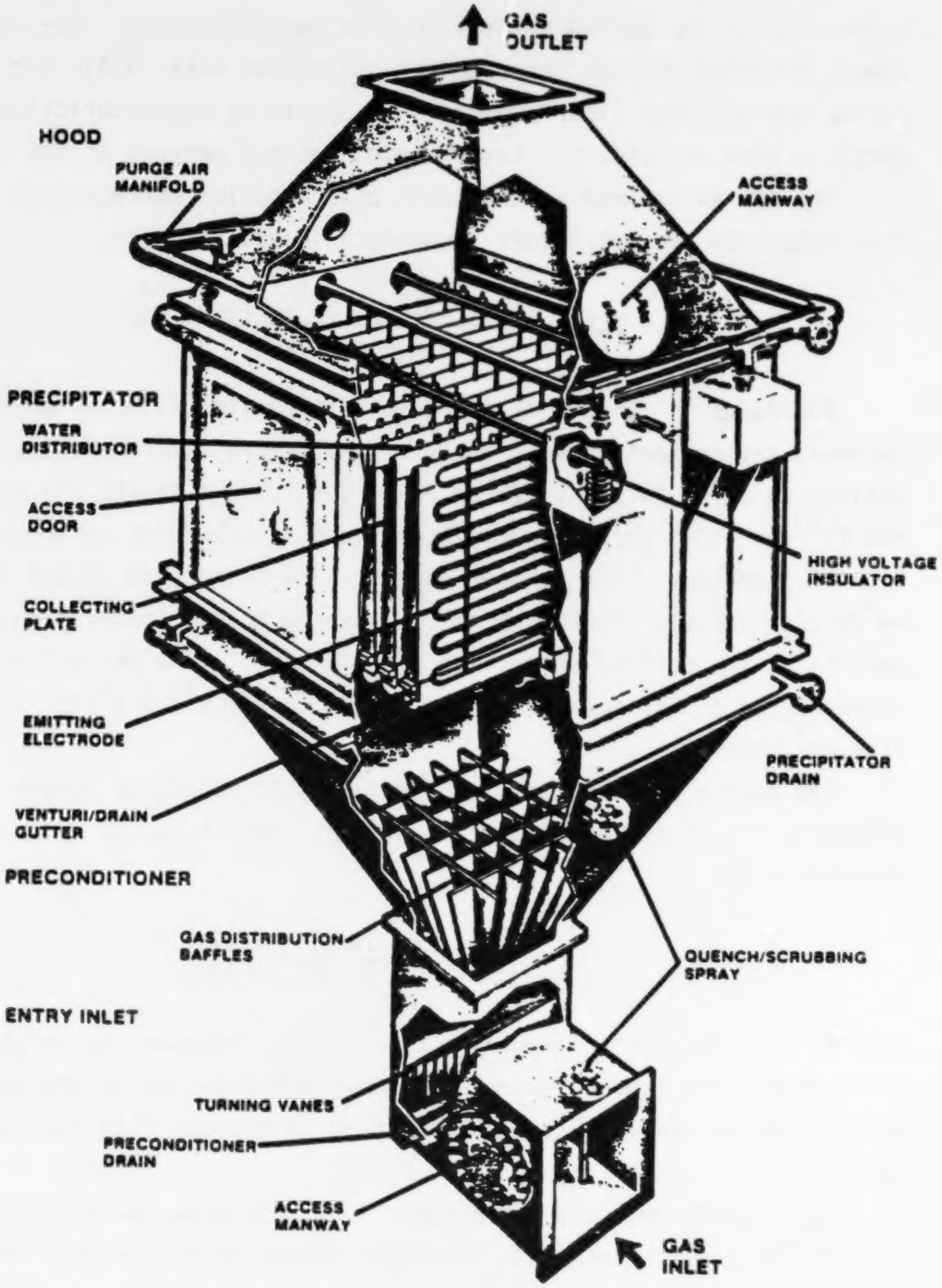
GAS OUTLET
HOOD
PURGE AIR MANIFOLD
ACCESS MANWAY
PRECIPITATOR
WATER DISTRIBUTOR
ACCESS DOOR
HIGH VOLTAGE INSULATOR
COLLECTING PLATE
EMITTING ELECTRODE
PRECIPITATOR DRAIN
VENTURI/DRAIN GUTTER
PRECONDITIONER
GAS DISTRIBUTION BAFFLES
QUENCH/SCRUBBING SPRAY
ENTRY INLET
TURNING VANES
PRECONDITIONER DRAIN
ACCESS MANWAY
GAS INLET

Figure 4-7. Flat-plate type wet ESP.[8]

The performance of a wet ESP is affected by design and operating properties of the system as well as flue gas conditions. Key design characteristics include the specific collection area (SCA), the aspect ratio, and gas flow distribution. Key operating characteristics include particle size resistivity, temperature, and H_2O content of the gas stream.

The SCA is defined as the ratio of collection surface area to the gas flow rate into the collector. Expressed in metric units,

$$\text{SCA} = \frac{\text{total collection surface, m}^2}{1{,}000\ \text{m}^3/\text{h}} \qquad \text{(Eq. 4-1)}$$

Increases in the SCA of a precipitator design will, in most cases, increase the collection efficiency of the precipitator. Most conservative designs call for an SCA of 20 to 25 m^2 per 1,000 m^3/h (km^3/h) (350 to 400 ft^2 per 1,000 acfm [kacfm]) to achieve a collection efficiency of more than 99.5 percent. The general range of SCA is between 11 and 45 m^2 per km^3/h (200 and 800 ft^2 per kacfm), depending on precipitator design conditions and desired collection efficiency.[8,9] The wet ESP currently operating on a nodulizing kiln has an SCA of about 9.3 $m^2/km^3/h$ (170 ft^2/kacfm).

The aspect ratio (AR) is the ratio of the effective length to the effective height of the collector surface. The AR can be calculated using Equation 4-2.

$$\text{AR} = \frac{\text{effective length, m (ft)}}{\text{effective height, m (ft)}} \qquad \text{(Eq. 4-2)}$$

Typical AR's for ESP's range from 0.5 to 2.0. However, for high-efficiency ESP's (those having collection efficiencies of >99 percent), the AR used in precipitator design should be greater than 1.0, usually 1.0 to 1.5.

Gas flow through the ESP chamber should be slow and evenly distributed through the unit. The gas velocities in the duct leading into the ESP are generally between 6 to 24 m/s (20 and 80 ft/s). The gas velocity into the ESP must be reduced for adequate particle collection. This velocity reduction is achieved by using an expansion inlet plenum. The inlet plenum contains perforated diffuser plate openings to distribute the gas flow evenly through the precipitator. Typical gas velocities in the ESP chamber range from 0.6 to 2.4 m/s (2 to 8 ft/s). With an aspect ratio of 1.5, the optimum gas velocity is generally between 1.5 to 1.8 m/s (5 to 6 ft/s).

Resistivity is a measure of how difficult it is for a given particle to conduct electricity. The higher the measured resistivity (the value being expressed in ohm-cm), the harder it is for the particle to transfer the charge. Resistivity is influenced by the chemical composition of the gas stream and PM, the moisture content of the gas stream, and the temperature. Resistivity must be kept within reasonable limits for the ESP to perform as designed. The preferred range is 10^8 to 10^{10} ohm-cm.

Temperature is important because it affects resistivity and because it affects the condensation of Po-210. The use of a spray tower upstream from the scrubber will reduce the temperatures of the gas stream to about 70°C (150°F) and condense virtually all of the Po-210 in the gas stream.

4.1.4 SD/FF Systems

The SD/FF system is a multipollutant control system that is used to control PM emissions as well as to reduce the concentrations of acid gases in the stream. The SD/FF comprises two primary components--a spray dryer or absorber and a pulse jet fabric filter. In the spray dryer, the gas stream is cooled, vapor-phase Po-210 and Pb-210 condense on the surfaces of the PM in the gas stream and the lime that is injected into the spray dryer, and HF and SO_2 are absorbed in the lime slurry. The evaporative cooling in the spray dryer results in a dry, particulate-laden gas stream. The PM is removed from the gas stream in a pulse jet fabric filter. The paragraphs below describe the spray dryer system and the fabric filter separately.

In the spray drying process, sorbent is injected into the gas stream as a liquid or liquid slurry spray with sufficient moisture to promote rapid adsorption of the acid gases. However, the evaporative cooling of the acid gases vaporizes the moisture from the sorbent and produces a dry PM which must be collected. Systems that have been installed on combustors and furnaces have used varied mechanisms to introduce sorbent to the gas stream. Sorbent may be injected through liquid nozzles or rotary atomizers. It may be screw-fed or pneumatically blown in dry and rewetted by water-only nozzles, or it may be injected wet or dry into a fluidized bed with overhead water sprays. The ensuing discussion focuses upon one of these systems--the atomizing spray dryer absorber--because it is the most likely to be applied to metallurgical furnaces such as those in elemental phosphorus plants.

Figure 4-8 illustrates a typical spray drying process.[10] Lime is slaked, mixed with water, and then pumped as a slurry to a feed tank. Depending on the inlet concentration of pollutants, slurry is metered into the spray absorber (shown with a rotary atomizer in Figure 4-8). Flue gas heat is sufficient to dry the slurry into a solid powder within the reactor vessel, and some of the solids are collected in the bottom of the absorber vessel while the remainder are collected in the particle collector. Recycle of solids back to the feed tank may be selected as an option if sorbent utilization is very low or higher removals of gaseous pollutants are desired.

The lime feed rate to the spray dryer affects acid gas removal efficiencies; it also has a significant impact on cost. The control of HF and SO_2 are governed by the following chemical reactions.

$$Ca(OH)_2+SO_2 \rightarrow CaSO_3 \cdot 1/2\ H_2O+1/2\ H_2O \qquad \text{(Eq. 4-3)}$$

$$CaSO_3 \cdot 1/2\ H_2O+1/2\ O_2+3/2\ H_2O \rightarrow CaSO_4 \cdot 2\ H_2O \qquad \text{(Eq. 4-4)}$$

$$Ca(OH)_2+2HF \rightarrow CaF_2 \cdot 2\ H_2O \qquad \text{(Eq. 4-5)}$$

Data collected from combustion processes indicate that acceptable levels of acid gas control can be achieved at a 1.5:1 stoichiometric ratio of lime to HF and SO_2 combined. At that stoichiometric ratio, the requirements for lime addition are 1.7 kg lime per kg of SO_2 and 2.8 kg of lime per kg of HF emitted from the kiln.

Temperatures should be maintained at levels that promote condensation of volatile metals such as Po-210 and Pb-210 and, at the same time, prevent liquid condensation. The control of this process to achieve optimal temperatures is relatively simple. The spray dryer outlet flue gas temperature and moisture are controlled to a narrow range. Sorbent is

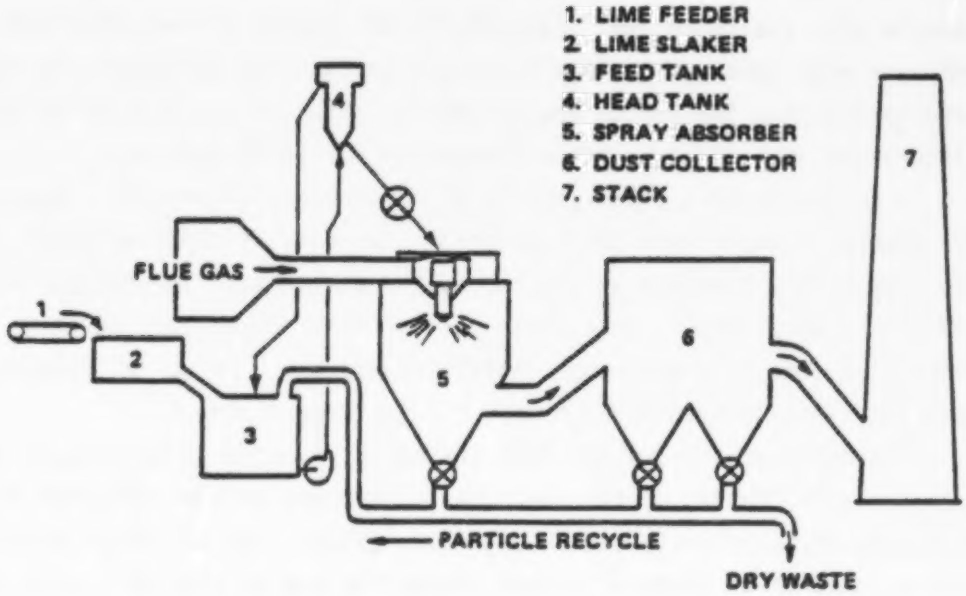
1. LIME FEEDER
2. LIME SLAKER
3. FEED TANK
4. HEAD TANK
5. SPRAY ABSORBER
6. DUST COLLECTOR
7. STACK
FLUE GAS
1
2
3
4
5
6
7
PARTICLE RECYCLE
DRY WASTE

Figure 4-8. Spray dryer/fabric filter system.[10]

thereby precluded from contacting downstream surfaces as a wet powder leading to solids buildup. The system also is operated well above the dewpoints of any acid gases. Temperatures are typically controlled at 110° to 160°C (230° to 320°F) by limiting the amount of water injected.[10]

The particulate matter that leaves the spray dryer must be controlled by a high-efficiency PM collector. The control device typically employed on metallurgical furnaces is a fabric filter. Generally, fabric filters are classified by the type of cleaning mechanism that is used to remove the dust from the bags. The three types of units are mechanical shakers, reverse air, and pulse jet. Essentially all fabric filters that are employed with spray dryers are pulse jet units. The paragraphs below briefly describe the design and operating characteristics of pulse jet filters and identify key design parameters for SD/FF systems.

A schematic of a pulse jet filter is shown in Figure 4-9. Bags in the baghouse compartment are supported internally by rings or cages. Bags are held firmly in place at the top by clasps and have an enclosed bottom (usually a metal cap). Dust-laden gas is filtered through the bag, depositing dust on the outside surface of the bag. Pulse jet cleaning is used for cleaning bags in an exterior filtration system.

The dust cake is removed from the bag by a blast of compressed air injected into the top of the bag tube. The blast of high pressure air stops the normal flow of air through the filter. The air blast develops into a standing or shock wave that causes the bag to flex or expand as the shock wave travels down the bag tube. As the bag flexes, the cake fractures and deposited particles are discharged from the bag. The shock wave travels down and back up the tube in approximately 0.5 seconds.[11]

The blast of compressed air must be strong enough for the shock wave to travel the length of the bag and shatter or crack the dust cake. Pulse jet units use air supplied from a common header which feeds into a nozzle located above each bag. In most baghouse designs, a venturi sealed at the top of each bag is used to create a large enough pulse to travel down and up the bag. The pressures involved are commonly between 414 kPa and 689 kPa (60 and 100 psig). The importance of the venturi is being questioned by some pulse jet baghouse vendors. Some baghouses operate with only the compressed air manifold above each bag.[11]

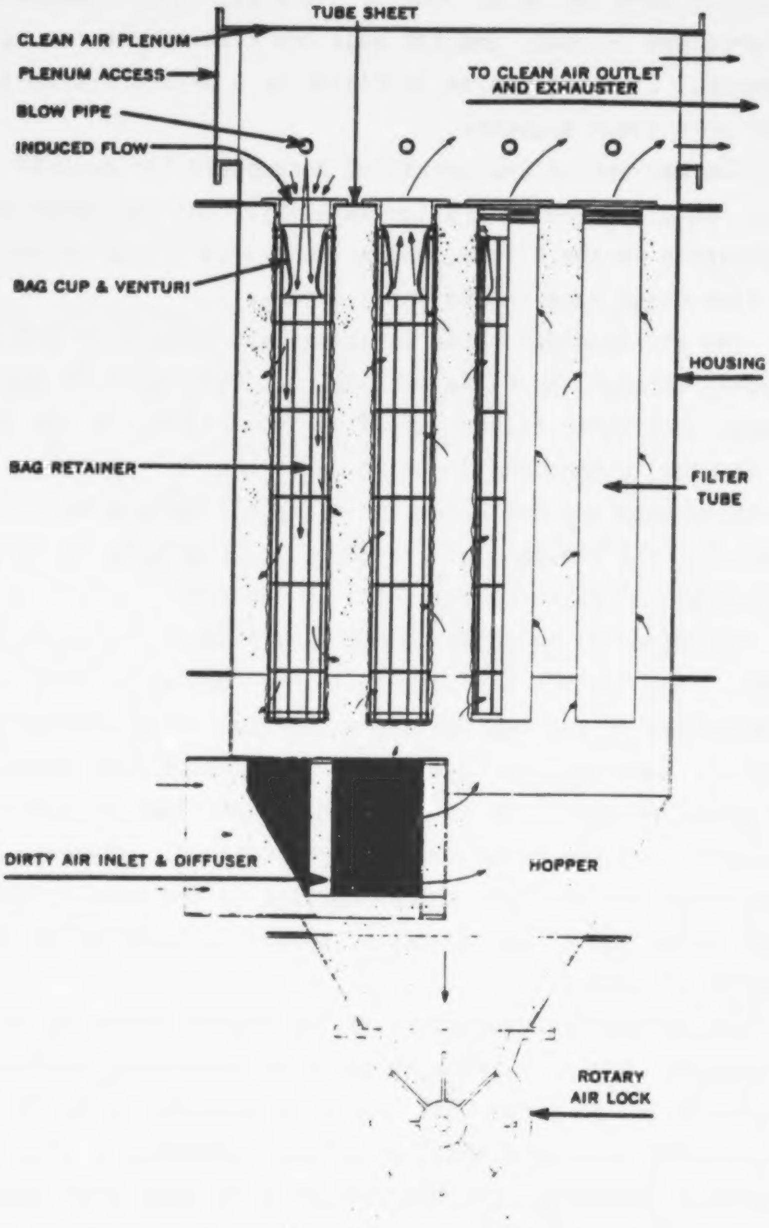
TUBE SHEET
CLEAN AIR PLENUM
PLENUM ACCESS
TO CLEAN AIR OUTLET AND EXHAUSTER
BLOW PIPE
INDUCED FLOW
BAG CUP & VENTURI
HOUSING
BAG RETAINER
FILTER TUBE
DIRTY AIR INLET & DIFFUSER
HOPPER
ROTARY AIR LOCK

Figure 4-9. Pulse-jet fabric filter.[2]

Most pulse jet filters use bag tubes that are 10 to 15 cm (4 to 6 in.) in diameter. Typically, the bags are 3.0 to 3.7 m (10 to 12 ft) long, but they can be as long as 7.6 m (25 ft).[11] Generally, these bags are arranged in rows, and the bags are cleaned one row at a time in sequence. Cleaning can be initiated by a pressure drop switch, or it may occur on a timed sequence.

The key design and operating parameters for a SD/FF are the air-to-cloth ratio (or the filtration velocity), the bag material, operating temperature in the filter, operating pressure drop across the filter, and the lime usage rate in the spray dryer.

The air-to-cloth ratio is actually a measure of the superficial gas velocity through the filter medium. It is a ratio of the flow rate of gas through the fabric filter (at actual conditions) to the area of the bags and is usually measured in units of m^3/min^2 of cloth area ($acfm/ft^2$). No operating data are available for elemental phosphorus systems, but generally, the air-to-cloth ratio on SD/FF systems is in the range of 1.5 to 3 $m^3/min/m^2$ (5 to 10 $acfm/ft^2$) of bag area.[10]

Bag material selection generally is based on prior experience of the vendor. Key factors that generally are considered are: cleaning method, abrasiveness of the particulate matter and abrasion resistance of the material, expected operating temperature, potential chemical degradation problems, and cost. No information was obtained on types of material typically used for metallurgical applications. However, given the temperature and acid gas concentrations in the nodulizing kiln exhaust gases, some type of teflon-coated synthetic material is likely to be the material of choice.

The operating temperature of the fabric filter is of critical importance. Since the exhaust gas from nodulizing kilns or calciners can contain HF and SO_2, the unit should be operated at sufficiently high temperatures to ensure that no surface temperatures drop below the acid dewpoint. Otherwise, condensation of acid gases will result in corrosion of the housing or bags. Gas temperatures maintained at about 150°C (300°F) ensure that no surfaces are cooled below the dewpoint. At the same time, temperatures should be as low as possible to ensure complete condensation of Po-210. Above a maximum temperature that is dependent on filter type, bags will degrade or in some cases fail completely. Gas temperatures should be kept safely below the allowed maximum. Temperature of the inlet gas to the fabric filter is maintained at appropriate levels by adjusting the liquid flow rate to the spray dryer.

Pressure drop in fabric filters generally is maintained within a narrow range. For pulse jet filters, the upper end of the range typically is 2.5 to 3.7 kPa (10 to 15 in. w.c.). Pressure drops below the minimum indicate that either (1) leaks have developed, or (2) excessive cleaning is removing the base cake from the bags. Either phenomenon results in reduced performance. Pressure drops greater than the maximum indicate that either (1) bags are "blinding," or (2) excessive cake is building on the bags because of insufficient cleaning. The primary problem that results from excess pressure drop is reduced flow through the system and positive pressure in the kiln. Over time, high pressure drops also lead to bag erosion and degradation.

4.1.5 HEPA Filters

High-efficiency particulate air filters are commonly used in industries that require high-efficiency removal of particulate matter in the submicron range. These stringent levels of air cleaning may be necessary either to protect human health or to produce a particulate-free work environment. The HEPA technology is used extensively in nuclear, military, pharmaceutical, aerospace, microelectronics, research, and health care applications.

By definition, a HEPA filter is a throwaway, extended-pleated-medium, dry filter with (1) a rigid casing enclosing the full depth of the pleats, (2) a minimum particle removal efficiency of 99.97 percent for 0.3-μm thermally generated, monodisperse dioctylphthalate (DOP) particles, and (3) a maximum pressure drop of 0.25 kPa (1.0 in. w.c.) when clean and operated at rated airflow capacity.[12]

Diffusion and inertial impaction are the primary mechanisms for particle collection by HEPA filtration. The effectiveness of these mechanisms varies with particle size, airflow velocity through the medium, and, to some extent, particle density. At a constant air velocity, the diffusion mechanism predominates as particle size decreases; inertial impaction accounts for collection of larger sized particles. For a given particle size, the effectiveness of diffusion decreases and inertial collection increases as flow velocity increases. For a given particle size and velocity, an increase in particle density decreases the effectiveness of diffusion and increases the effectiveness of the inertial effect.

The HEPA filter efficiencies are based on numbers of particles removed, not on mass removed as is common with air pollution control devices. Parameters that are commonly used to describe HEPA filtration performance are the efficiency, penetration, and decontamination factor (DF). Each of these terms is defined below.

$$\text{Efficiency, percent} = (U-D)/U * 100 \qquad \text{(Eq. 4-6)}$$

$$\text{Penetration, percent} = (D/U) * 100 \qquad \text{(Eq. 4-7)}$$

$$\text{Decontamination factor} = U/D \qquad \text{(Eq. 4-8)}$$

where:

U = upstream particle count
D = downstream particle count

The DF is commonly used to compare filter performance because it demonstrates differences between filter performances more distinctly than either efficiency or penetration. For example, a 99.995 percent efficient filter (DF=20,000) is twice as effective as a 99.99 percent efficient filter (DF=10,000), and six times as effective as a 99.97 percent efficient filter (DF=3,333).

Within a single filter, performance varies depending on particle size. Lowest removal efficiencies (highest penetration) occur for particles in the 0.07- to 0.12-μm range (Figure 4-10). Design efficiencies are determined by challenging the filter with 0.3 μm mondispersed DOP particles. Filters are designed to achieve efficiencies ranging from 99.97 percent to 99.999 percent for this particle size.

The properties of a HEPA filter that are of primary concern when designing a system are its particle collection efficiency, airflow capacity, and pressure drop. The HEPA filters are available in a range of sizes and capacities. The largest capacity filter available is

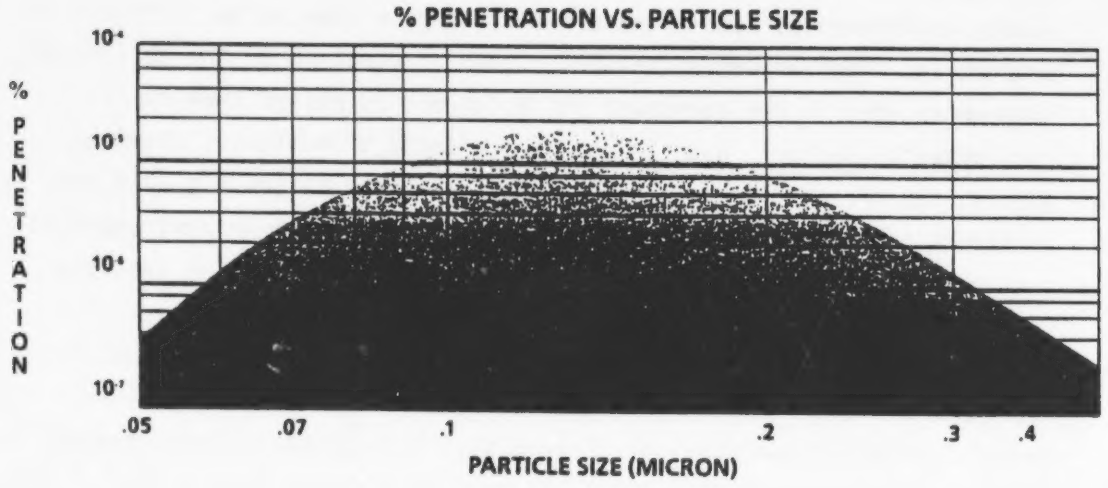

Figure 4-10. The HEPA filter performance curve.

(0.6 m)x(0.6 m)x(0.3 m) ([24 in.]x[24 in.]x[11.5 in.]) and is rated at 57 m^3/min (2,000 ft^3/min) airflow. To accommodate large airflows, multiple filters are arranged in banks. Filters usually are removed and replaced when the pressure drop across the filter reaches twice the clean filter pressure drop, i.e., 0.5 kPa (2.0 in. w.c.).

The environmental conditions to which the filter system will be exposed must be considered when designing a HEPA filter system. Key environmental parameters requiring consideration are temperature, moisture, corrosion potential, and vibration potential. The combined influence of these parameters will affect the selection of a filter for a particular application. Unfortunately, the application of HEPA filters to severe environmental conditions often requires a compromise in filter properties. Manufacturers frequently have information on the ability of components used in the construction of filters to resist chemical or environmental factors, but the combined effects of humidity, chemical agents, and heated air upon filters and the interrelationship with the construction materials are typically unknown. Destructive environmental testing is recommended when the suitability of a filter for a specific environment is in doubt.

A HEPA filter consists of five components: the filter medium, the medium separators (optional), the media-to-frame sealant, the filter frame, and the filter housing. Figure 4-11 is a schematic of a typical filter and arrangement of multiple filters in a filter bank.

The filter medium may be folded and supported by corroguated metal separators, typically aluminum, or be preformed and self-supporting. It may be composed of asbestos, cellulose, microglass fibers, plastics, or ceramic materials, or blends thereof. Fire-resistant filter media are usually composed of fiberglass, sometimes with a small percentage of asbestos added to improve resistance to HF, or ceramic material. Proprietary media designed for enhanced HF resistance are available. The HEPA filter media are rated at 100 percent relative humidity conditions and will tolerate both high humidity and direct wetting. However, excessive amounts of moisture, either from airborne droplets or condensation on the element can completely plug the filter and result in failure by overpressure. The important factors in moisture resistance are the wet

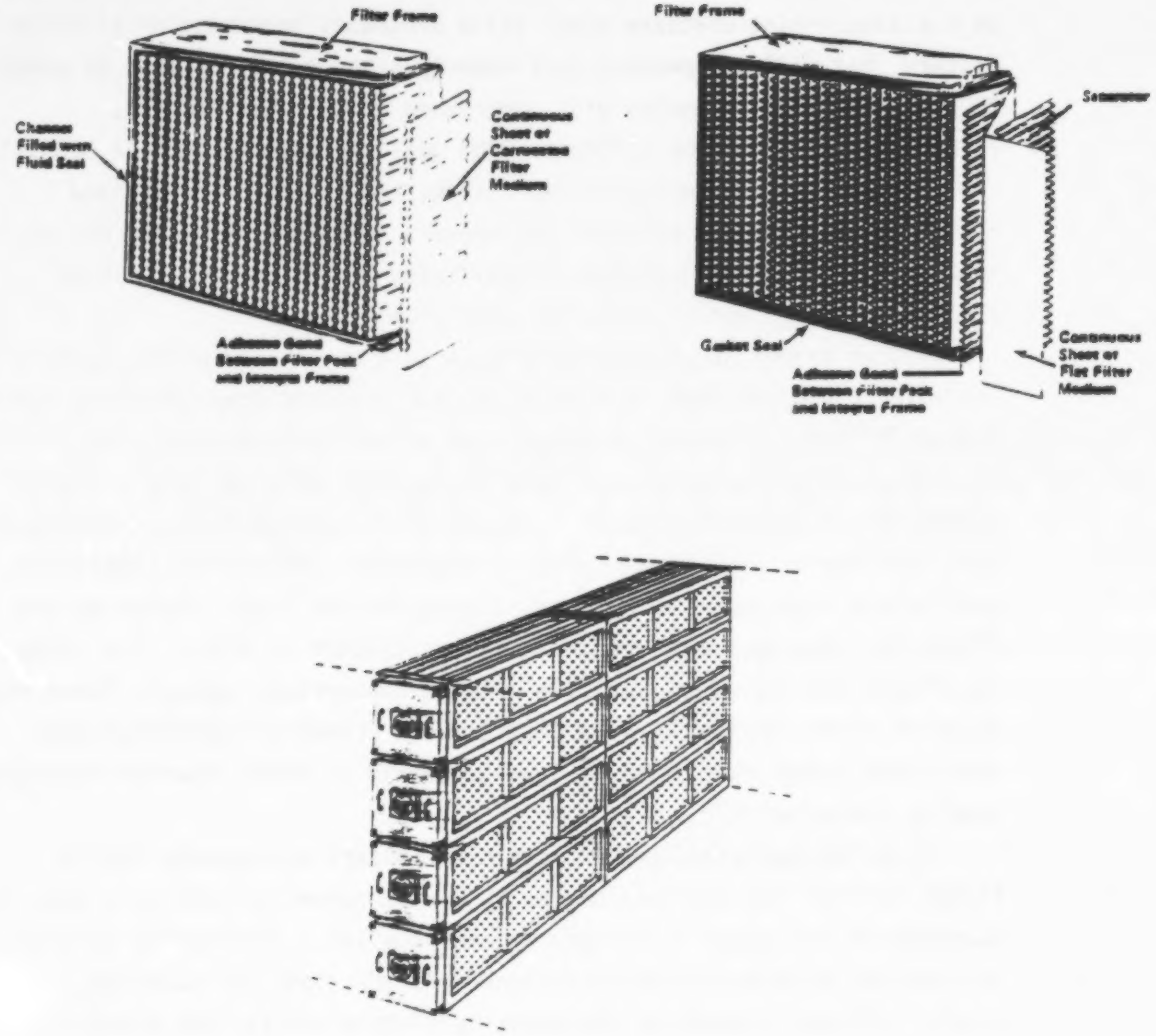
Filter Frame
Channel Filled with Fluid Seal
Continuous Sheet of Corrugated Filter Medium
Adhesive Bond Between Filter Pack and Integral Frame
Filter Frame
Separator
Gasket Seal
Adhesive Bond Between Filter Pack and Integral Frame
Continuous Sheet of Flat Filter Medium

Figure 4-11. Examples of HEPA filter systems.[12]

tensile strength of the media, which is related to media rupture under high overpressure, and its water repellency, which is related to the plugging that produces the high overpressure.

The sealant is the most sensitive component of the filter apparatus with respect to environmental conditions. The sealant traditionally used to seal the fiber core into the frame is a heat- and moisture-resistant elastomeric adhesive. Commonly used sealants are chemically expanded self-extinguishing urethane foam; solid urethane; neoprene; or silicone. Filters that will be operated continuously at high temperatures of about 200°C (400°F) may be sealed with compressed glass-fiber matting, refractory adhesives, or silicone. The qualities desirable in a sealant are (1) moisture and corrosion resistance, (2) ability to withstand radiation exposure and alternating exposure to heat and cold or dry to humid air, and (3) maintenance of seal integrity at design operating conditions and potential transient conditions.

Filter frames are available in a variety of fire-retardant materials including rigid urethane, 1.9-cm (0.75 in.) exterior grade particle board, 1.9-cm (0.75-in.) plywood, 14 gauge Type 409 or 304 stainless steel, or zinc or aluminum coated steel. Metal frames are selected when a high degree of corrosion resistance is required, or when continuous wetting or high humidity at high temperatures is expected. Under these conditions, wood frames have been found to absorb moisture and swell, rupturing the filter-to-frame seal and permitting filter by-pass to occur. The sides of the filter are sealed to the frame with an appropriate sealant. When high sound or vibration levels are expected, wood frames are preferred over metal ones (other factors being equal) because of their superior vibration damping characteristics.

Prior to operation, one or more HEPA filters are mounted into a filter housing that consists of the requisite number of holding frames to accommodate the number of filters to be installed. The housing typically is zinc- or aluminum-coated corrosion-resistant steel, or stainless steel. Critical aspects of the mounting fixture are (1) the structural integrity; (2) tolerances on dimensions, flatness, alignment, and the finish of the filter seating surface; (3) the method of sealing the mounting fixture into the filter housing; (4) rigidity of filter clamping devices; and (5) the degree and uniformity of filter gasket compression.

When a corrosive environment such as that found in the nodulizing kiln exhaust exists, stainless steel is recommended for ductwork and filter housings. Even this material may be insufficient in highly corrosive atmospheres, and epoxy- or vinyl-coated stainless steel or fiber-reinforced plastics may be necessary.

In severe applications like those in elemental phosphorus plants, it may be necessary to modify and improve the environment to which the system will be exposed by pretreating the air prior to entry into the HEPA system. Scrubbers may be employed upstream to remove corrosive constituents such as inorganic acids. Consideration must be given to moisture carryover if wet scrubbers are used. Demisting devices should be added downstream of wet scrubbers to reduce the moisture content of the gas stream, and the gas stream should be reheated to prevent condensation from occurring on the filter element. A prefilter system may be added upstream of the HEPA system to reduce particulate loading and increase HEPA filter life. Prefilters should be provided if the particulate loading exceeds 2.3 mg/m^3 (0.001 gr/acf). The decision to install prefilters should be based on providing the best operational balance between HEPA filter life and capital and maintenance costs for the prefilters. Generally, the use of a prefiltration system will extend HEPA life by a factor of 2. Estimates of filter life for HEPA filters are presented as a part of the cost analyses in Section 4.3.

The principal costs in operating a HEPA filtration system are energy costs (i.e., fan power), replacement filters, and labor. The frequency of changing the filters is the primary factor affecting these costs. For elemental phosphorus applications, replacement filters and labor may constitute over 90 percent of the total cost of owning a system (including capital costs) over a 20-year period.

4.2 PERFORMANCE OF ALTERNATIVE CONTROL TECHNOLOGIES

One of the primary objectives of this study is to assess the ability of the alternative control technologies to reduce Po-210 and Pb-210 emissions from nodulizing kiln or calciner operations. This subsection presents available information on the performance of each of the four primary control techniques and establishes procedures for estimating Po-210 and Pb-210 control efficiencies for the specific control alternatives that are evaluated on a plant-by-plant basis in Section 5.0. In general, these procedures are based on estimates of overall PM control efficiencies or particle-size-specific control efficiencies. The Po-210 and Pb-210 efficiencies then can be estimated on the basis of the Po-210 or Pb-210 concentrations in the PM or in specific size fractions. To the degree that emission data are available, the validity of the estimating procedures was evaluated by comparing estimated efficiencies to measured control efficiencies. Each of the four control techniques is addressed in individual subsections below.

4.2.1 Venturi Scrubbers

The control efficiency of venturi scrubbers is highly dependent on particle size distribution and on the L/G ratio and pressure drop across the scrubber. The penetration across a venturi scrubber (where penetration is 1 minus control efficiency) for a particle of specific diameter can be estimated by the following equations which was developed by Yung and Calvert.[1] The equations presented below are used to develop performance estimates for venturi scrubber control options in Section 5.

$$\ln Pt(d_p) = -B\,\frac{4\,K_{po}+4.2-5.02\,K_{po}^{0.5}\left(1+\frac{0.7}{K_{po}}\right)\tan^{-1}{\frac{K_{po}}{0.7}}^{0.5}}{K_{po}+0.7} \qquad \text{(Eq. 4-10)}$$

where:

$Pt(d_p)$ = penetration for one particle size

B = parameter characterizing the liquid-to-gas ratio, dimensionless

K_{po} = inertial parameter at throat entrance, dimensionless

Note: Equation 4-9 was developed assuming that the venturi has an infinite-sized throat length. This is valid only when ℓ, as defined below, is greater than 2.0.

$$\ell = \frac{3\ell_r C_D \rho_s}{2D_d \rho_l} \qquad \text{(Eq. 4-10)}$$

where:

ℓ = throat length parameter, dimensionless

ℓ_r = venturi throat length, cm

C_D = drag coefficient for the liquid at the throat entrance, dimensionless

ρ_S = gas density, g/cm^3

D_d = droplet diameter, cm

ρ_l = liquid density, g/cm^3

$$D_d = \left(\frac{50}{v_{gt}}\right)+91.8\ (L/G)^{1.5} \qquad \text{(Eq. 4-11)}$$

where:

D_d = droplet diameter, cm

v_{gt} = gas velocity in the throat, cm/s

L/G = liquid-to gas ratio, dimensionless

$$B = (L/G)\ \frac{\rho_l}{\rho_g C_D} \qquad \text{(Eq. 4-12)}$$

where:

B = parameter characterizing liquid-to-gas ratio, dimensionless

L/G = liquid-to-gas ratio, dimensionless

ρ_l = liquid density, g/cm^3

ρ_g = gas density, g/cm^3

C_D = drag coefficient for the liquid at the throat entrance, dimensionless

$$K_{po} = \frac{d_p^{\,2}\ v_{gt}}{9\ \mu_g d_d} \qquad \text{(Eq. 4-13)}$$

where:

K_{po} = inertial parameter at the throat entrance, dimensionless

d_p = particle aerodynamic resistance diameter, cmA

v_{gt} = gas velocity in the throat, cm/s

μ_g = gas viscosity, g/cm • s

d_d = droplet diameter, cm

$$K_{po} = \frac{d_{og}^{\,2}\ v_{gt}}{9\ \mu_g d_d} \qquad \text{(Eq. 4-14)}$$

where:

K_{po} = inertial parameter at the throat entrance, dimensionless
d_{pg} = particle aerodynamic geometric mean diameter, cmA
v_{gt} = gas velocity in the throat, cm/s
μ_g = gas viscosity, g/cm • s
d_d = droplet diameter, cm

$$C_D = 0.22 + \frac{24}{N_{Reo}}(1+0.15N_{Reo}^{0.6}) \qquad \text{(Eq. 4-15)}$$

where:

C_D = drag coefficient for the liquid at the throat entrance, dimensionless
N_{Reo} = Reynolds number for the liquid droplet at the throat inlet, dimensionless

$$N_{Reo} = \frac{v_{gt}D_d}{\nu_g} \qquad \text{(Eq. 4-16)}$$

where:

N_{Reo} = Reynolds Number for the liquid at the throat entrance, dimensionless
v_{gt} = gas velocity in the throat, cm/s
ν_g = gas kinematic viscosity, cm^2/s
D_d = droplet diameter, cm

$$d_{pg} = d_{pg}(C_f x \ell_p)^{0.5} \qquad \text{(Eq. 4-17)}$$

where:

d_{pg} = particle aerodynamic geometric mean diameter, μmA
d_{ps} = particle physical, or Stokes, diameter, μm
C_f = Cunningham slip correction factor, dimensionless
ρ_p = particle density, g/cm^3

$$C_f = 1 + \frac{(6.21 \times 10^{-4})T}{d_{ps}} \qquad \text{(Eq. 4-18)}$$

where:

C_f = Cunningham slip correction factor, dimensionless
T = absolute temperature, K
d_{ps} = particle physical, or Stokes, diameter, μm

$$v_{gt} = \left[\frac{1.21 \times 10^3\ \Delta P}{(L/G)}\right]^{1/2} \qquad \text{(Eq. 4-19)}$$

where:

v_{gt} = gas velocity in throat, cm/s
ΔP = pressure drop, cm H_2O
L/G = volumetric liquid-to-gas ratio, dimensionless

In general, only the pressure drop and L/G ratio were allowed to vary in the analyses conducted during this study. All other values were held constant at the following levels:

ρ_ℓ = 1,000 kg/m^3
ρ_g = 1.0 kg/m^3
μg = 2.0×10^{-4} g/cm•s
ν_g = 0.2 cm^2/s

Emission testing was conducted recently at the inlet and outlet of a high-energy venturi scrubber at the Monsanto facility in Soda Springs, Idaho. The data in Section 3.0 indicate that the Po-210 emissions were measured at 23 nCi/dscm at the inlet and 0.95 nCi/dscm at the outlet, a reduction of about 96 percent. The particle size distribution estimates from the 1988 EPA tests at the Monsanto spray tower outlet was used to estimate the Po-210 control efficiency using the above equations. The results, which are tabulated in Table 4-1, estimate that the overall efficiency of the venturi scrubber in controlling Po-210 would be about 75 percent, a level that is significantly less than the measured value obtained by Monsanto. Two factors may have contributed to this large difference as described below.

First, the data in Table 4-1 illustrate the sensitivity of these calculations to the particle size distribution, particularly the distribution in the submicron fraction. The particle size distribution that was used for these calculations introduces uncertainty to the

TABLE 4-1. ESTIMATED EFFICIENCY OF MONSANTO SCRUBBER

Particle diameter		Po-210 fraction	Fractional penetration	Total penetration
Range	Assumed mean			
	A	B	C	BxC
<0.5	0.35	0.600	0.397	0.238
0.5-0.9	0.67	0.265	0.034	0.0090
0.9-1.5	1.26	0.075	0.0011	0.00008
1.5-3	2.12	0.040	0.000097	0.000004
3-10	5.48	0.018	--	--
>10	10	0.012	--	--
TOTAL				0.25

analyses because the particle size was measured in the ductwork between the spray tower and the venturi. This high moisture stream from the spray tower is difficult to sample, and the inherent difficulties associated with particle size sampling in the high moisture exhaust stream can result in significant measurement errors. If the actual particle size at the venturi inlet is different than that assumed for the calculation, the model will produce biased results.

Second, the measurements of PM particle size at the venturi inlet and outlet indicate that the efficiency of the venturi is uniform overall particle size ranges. In light of the strong dependency of venturi scrubber performance on particle size suggested by the performance model and generally supported by other venturi scrubber test data, this finding is quite surprising. The estimated efficiency of 95 percent or greater in particles less than 0.5 μm in size is particularly surprising. Consequently, the measured efficiency may be biased high and should be used with caution.

In light the differences in the predicted and measured results at Monsanto, analyses based on a combination of measured performance at Monsanto and FMC and estimated performance based on the Yung/Calvert model were selected for estimating venturi scrubber performance. The estimated performance of the Monsanto and FMC is scrubbers presented in Table 4-2. The model is well established in the technical literature and generally is used by vendors for scrubber design. Because the analysis are somewhat uncertain the results presented in Section 5 should be interpreted with caution because they are highly sensitive to particle size distribution and measurement limitations.

4.2.2 Wet ESP's

For applications of ESP's to a specific type of industrial process such as elemental phosphorus nodulizing kilns or calciners, the primary design factor that affects ESP performance is the SCA, which is a ratio of the collection plate area to the volumetric flow through the ESP. This relationship is incorporated in the Deutsch-Anderson equation for estimating ESP efficiency:

$$\eta = 1\text{-}\exp\left[-w(A/Q)\right] \qquad \text{(Eq. 4-20)}$$

TABLE 4-2. ESTIMATES OF VENTURI SCRUBBER PERFORMANCE

Facility	Pressure drop	Po-210		Pb-210		Efficiency	
		Inlet	Outlet	Inlet	Outlet	Po-210	Pb-210
Monsanto[a]	High	4,052	172	1,280	40.58	96	97
FMC[b]	Maximum[c]	1,075	1,065	43.6	26.1	Neg.	40
	Typical[d]	1,075	1,208	43.6	4.1	Neg.	91

[a] Reference 13.

[b] Reference 14.

[c] Adjustable low-energy throat venturi scrubber operated at system maximum ΔP.

[d] Adjustable throat low-energy venturi scrubber operated at typical operating ΔP.

where:

η = collection efficiency of the ESP
A = collecting plate area, m^2
Q = volumetric gas flow rate, m^3/s
w = migration velocity, m/s

The equation indicates that ESP collection efficiency increases with increasing values of the SCA and the migration velocity. The migration velocity is a function of the characteristics of the emission stream (particularly resistivity and particle size distribution) and wet ESP design parameters such as electrode arrangement and field strengths. Mathematically, the migration velocity can be estimated as:

$$w = S\ d_p\ k_c\ (\text{for } d_p \leq 5\ \mu m) \qquad \text{(Eq. 4-21)}$$

or

$$w = Sd_p\ (\text{for } d_p\ 5\ \mu m) \qquad \text{(Eq. 4-22)}$$

with

$$S = \frac{pE_cE_p}{12\ \pi\ \mu_g} \qquad \text{(Eq. 4-23)}$$

and

$$k_c = 1{+}0.172/d_p \qquad \text{(Eq. 4-23)}$$

where:

k_c = Cunninham correction factor, dimensionless
d_p = particle diameter, μm
p = 3D/D+2 where D is the dilectric constant (generally about 1 for air)
E_c = charging field strength, V/m
E_p = collecting field strength, V/M
μ_g = dynamic viscosity, g/cm•s
S = constant of proportionality

In practice, w is determined empirically based on test data from similar operations. For this study, the data from the 1983 EPA PM tests at Stauffer were used to develop estimates for w. The procedure is described below.

The first step in developing size-specific values for w was to estimate S, as a constant, based on the measured removal efficiency for the smallest fraction of PM at Stauffer. This constant value for S was then used to estimate size-specific migration velocities using Equations 4-21, 4-22, and 4-23. Table 4-3 summarizes the calculations used to determine S and presents estimates of w for the different size ranges of Po-210 emissions that were measured by EPA during the 1983 test program. These values of w are used to estimate control efficiencies for the different wet ESP control alternatives presented in Section 5.

Data from sites other than Stauffer are not available to assess the validity of the ESP model. However, the overall efficiency for Po-210 as measured by the EPA Method 5 tests at Stauffer was compared to the predicted efficiency based on the migration velocities reported in Table 3-2. The Method 5 tests measured an inlet concentration of Po-210 of 4.88 nCi/dscm and an outlet concentration of 1.61 nCi/dscm, a reduction of 67 percent. The model based on the impactor inlet data also estimated a 67 percent efficiency. Consequently, the model appears to yield consistent results for Stauffer. However, data are not available to determine how well the model can be generalized to other facilities and to control systems with different design parameters.

4.2.3 SD/FF Systems

Estimation of the efficiency of SD/FF systems in removing Po-210 and Pb-210 from the nodulizing kiln/calciner exhaust is much more complicated than was the case for venturi scrubbers or wet ESP's because information on the performance of these systems is quite scarce. No specific information was found on the removal of Po or Pb emissions from metallurgical furnace exhaust streams, and only limited information was obtained for Pb removal from combustion gas streams. Further, no general models are available on the performance of fabric filters, and data are not adequate to establish the effect of spray dryers on fabric filter performance. Hesketh notes that pulse jet PM emissions are unusual in that large particles may be released because of the agglomeration and the high cleaning energy.[15] Fractional particle size collection has little practical significance because size and number concentrations change radically over the filtration/cleaning cycle. For any specific

TABLE 4-3. SUMMARY OF ESP EFFICIENCY CALCULATIONS

1. Key input parameters (from test)

   $\eta = 0.558$
   $Q = 11.35\ m^3/s$
   $A = 364\ m^2$
   $d_p = 0.35\ \mu m$

2. Calculate w for d = 0.35 μm

   $w = [-\ln(1-\eta)]\ Q/A$
   $= 0.0255\ m/s$

3. Calculate k_c for dp = 0.35 μm

   $k_c = 1+0.172/0.35$
   $= 1.491$

4. Calculate S

   $S = w/d_p k_c = 0.489\ m/s \cdot \mu m$

5. Estimated values of w for different particle size ranges

d_p range, μm	d_p average, μm	w, m/s
<0.5	0.35	0.0255
0.5-0.9	0.67	0.0411
0.9-1.5	1.16	0.0651
1.5-3	2.12	0.112
3-10	5.48	0.268
>10	14	0.643

application, pulse jet collection efficiency is reported to be a function of inlet concentration, filtration velocity, pulse intensity, pulse duration, and pulse form.[15] Test data generally show that for a specific process with fabric filter operating parameters held at steady conditions, the outlet concentration of a pulse jet filter remains relatively constant. Under such conditions, the efficiency of the fabric filter is primarily a function of the total inlet concentration.

The findings described above suggest a procedure for estimating Po-210 and Pb-210 removal efficiencies for DS/FF systems based on the following assumptions:

1. The PM removal efficiency of a pulse jet fabric filter is not particle-size dependent;

2. At the temperatures achieved in a SD/FF system, essentially all Pb-210 and Po-210 is in particle form. Consequently, Po-210 and Pb-210 are removed by the fabric filter at the same efficiency as total PM;

3. Pulse jet fabric filters associated with SD/FF systems have been shown to achieve outlet PM concentrations in the range of 22 mg/dscm (0.01 gr/dscf) to below 2.2 mg/dscm (0.001 gr/dscf).[10,16] An outlet concentration of 22 mg/dscm (0.01 gr/dscf) will provide a conservative estimate of achievable PM control efficiency; and

4. The PM concentration at the inlet to the fabric filter is a combination of the solvent/acid gas reaction products and the PM emitted from the kiln.

Under the assumptions described above, the Po-210 and Pb-210 control efficiencies can be estimated as follows:

$$\text{Efficiency} = \frac{\text{Inlet PM concentration-Outlet PM concentration}}{\text{Inlet PM concentration}}$$

Obviously, no data are available to validate this procedure for nodulizing kilns or calciners. However, estimates of the efficiency were developed for a "model facility" under the following set of assumptions which are based on "typical" levels reported by elemental phosphorus facilities.

SO_2 concentration	1,200 ppmv
HF concentration	600 ppmv
PM concentration	4,000 mg/dscm

Under these assumptions, the estimated PM efficiency of the fabric filter is 99.87 percent. Although specific data are not available for metallurgical furnaces, data from SD/FF systems on municipal combustors indicate that efficiencies of about 99.9 percent can be achieved for volatile metals such as lead, arsenic, and cadmium.[16]

4.2.4 HEPA Filters

No data were located on the performance of HEPA filters on combustion systems or high-temperature furnaces. However, the fractional efficiency curve in Figure 4-10 indicates that a minimum efficiency of greater than 99.998 percent is achieved on particles in the 0.1 to 0.2 μm size range and that efficiencies generally are greater than 99.999 percent. For this study, the overall efficiency conservatively was assumed to be 99.998 percent.

4.3 COST OF CONTROL TECHNOLOGIES

The capital and annualized costs for each of the applicable control devices were determined following the guidelines established in Capital and Operating Costs of Selected Air Pollution Control Systems (GARD Manual) and in the EAB Cost Control Manual, Third Edition.[17,18] These manuals were prepared for the U. S. EPA to provide technical assistance to regulatory agencies in estimating the cost of air pollution control systems. The costs in the GARD Manual are based on December 1977 dollars and those in the EAB Cost Control Manual generally are based on 1986 dollars. The costs were adjusted to mid-1988 dollars using indices provided in Chemical Engineering and by the Bureau of Labor Statistics. Since the same basic procedure was used to cost each of the control techniques, a cost program was developed for use on a microcomputer. The paragraphs below describe the general cost methodology and key assumptions that were used to cost control options. Detailed assumptions for each operating facility are presented in Appendices A through E.

The costs were calculated assuming that each of the fine PM control measures, with the exception of the SD/FF, were added to control the exhaust from an existing spray tower. The existing system removes most of the large particles, quenches and cools the exhaust gas stream (thus, reducing gas volume and ensuring condensation of gaseous radionuclide emissions), and properly conditions the stream for treatment by the other options.

Capital costs include the direct and indirect costs to purchase and install the necessary ductwork, control device, fan systems, and stack. Direct capital costs include instruments, controls, taxes, freight, foundations, supports, erection and handling, electrical work, piping, insulation, painting, and site preparation. Indirect capital costs include engineering and supervision, construction and field expenses, construction fee, startup performance test, and contingencies. Table 4-4 presents the assumptions used for direct and indirect cost estimates based on information given in the GARD manual. All ductwork was sized based on a gas velocity of 20 meters per second (m/s) (4,000 ft/min). Site-specific estimates of the length of additional ductwork to connect the existing control system with the add-on control device were developed for the analyses in Section 5. Stack diameters were calculated to provide a stack gas velocity of 18 m/s (3,600 ft/min). All stack heights are assumed to be 15 m (50 ft) for the add-on equipment. With the exception of connecting ductwork, no special retrofit costs were included in the cost analyses. Based on information collected during plant visits, no retrofit problems are expected at these facilities.

Annualized costs include the total utility costs, the total operating labor costs, the total maintenance costs, the total overhead costs, the capital charges, and the total waste disposal costs. The annualized costs were based on 8,640 hours per year of operation (360 days). The utility costs reflect actual utility costs in the area of each facility as presented in Appendices A through E. The operating and maintenance labor costs were determined using an average hourly wage of $12/hour (h). The operating labor hours per shift for each control device were 4 h/shift for SD/FF's, 2 h/shift for scrubbers, and 1 h/shift for ESP's. The maintenance labor was assumed to be 1 h/shift for ESP's and scrubbers and 2 h/shift for SD/FF's.

The quantity of sludge or dry waste collected by the add-on control devices was determined based on the efficiency of particulate removal. In the case of the SD/FF, the quantity of lime added to the system also is considered. The cost to dispose of the waste in a secured landfill was

TABLE 4-4. ASSUMPTIONS USED IN ESTIMATING DIRECT AND INDIRECT COSTS[a]

	ESP	VS	FF
Direct costs			
Purchased equipment costs			
1. Control device	AR[b]	AR	AR
2. Auxiliary equipment	AR	AR	AR
3. Instruments and controls	0.10	0.10	0.10
4. Taxes	0.03	0.03	0.03
5. Freight	0.05	0.05	0.05
Total	1.00	1.00	1.00
Installation direct costs			
1. Foundations and supports	0.04	0.06	0.04
2. Erection and handling	0.50	0.40	0.50
3. Electrical	0.08	0.01	0.08
4. Piping	0.01	0.05	0.01
5. Insulation	0.02	0.03	0.07
6. Painting	0.02	0.01	0.02
7. Site preparation	AR	AR	AR
8. Facilities and buildings	AR	AR	AR
Total	1.67	1.56	1.72
Indirect costs			
Installation indirect costs			
1. Engineering and supervision	0.20	0.10	0.10
2. Construction and field expenses	0.20	0.10	0.20
3. Construction fee	0.10	0.10	0.10
4. Startup	0.01	0.01	0.01
5. Performance test	0.01	0.01	0.01
6. Model study	0.02	0.02	0.02
7. Contingencies	0.03	0.03	0.03
Total	2.24	1.91	2.17

[a] The numerical factors are multiplied by the purchased equipment costs to obtain total costs.

[b] AR = as required.

assumed to be $20/ton. The waste is considered to be hazardous for these calculations because of the concentration of radioactive material. (For comparison, it should be noted that the cost of disposing of nonhazardous wastes is approximately $5/ton.)

4.3.1 Venturi Scrubber Cost Assumptions

The capital and annualized costs for venturi scrubbers were based on procedures established in the GARD manual and on equipment costs established therein. Because of the large airflow encountered at most kilns, two identical scrubber systems in parallel were costed on one-half of the total exhaust stream. Radial fans were costed because of their ability to operate at high pressures and temperatures in an abrasive gas stream. The costs of the starter motor, direct and V-belt drives, and dampers are included in the fan costs. The corrosiveness (fluorides) of the gas stream entering a scrubber from the rotary kiln calciner requires that fabricated equipment cost estimates be based on the use of a combination of Hastelloy and Type 316 stainless steel. Plate thickness of the fan housing and ductwork was determined based on system static pressure. Details on the cost inputs for venturi scrubber control options for each facility are presented in Appendices A through E for the individual facilities.

4.3.2 Wet ESP Cost Assumptions

Capital and annualized costs for the ESP were based on an EPA cost update.[19,20] The primary factor, other than SCA, that affects ESP costs is material of construction. The corrosiveness (fluorides) of the gas stream entering an ESP from the rotary kiln calciner requires that fabricated equipment the ductwork and ESP housing be constructed of a corrosion resistant material. Costs for these components were based on the use of Type 316 stainless steel. Collecting electrodes also were assumed to be constructed from Type 316 stainless steel.

4.3.3 SD/FF Cost Assumptions

Spray dryer/fabric filter systems provide efficient collection of both condensible PM and acid gases. Key design parameters that affect system performance and costs are lime addition, gas temperature entering the FF, FF air-to-cloth ratio, and pressure drop through the system. Lime addition rates were calculated under the assumption of a 1.5:1

stoichiometric ratio of lime to HF and SO_2 combined. The gas temperature at the FF inlet was assumed to be 150°C (300°F). An air-to-cloth ratio of 1:1.2 m^2/m^3/min (4:1 ft^2/ft^3/min) and a system pressure drop of 3.1 kPa (12.5 in. w.c.) were used.

Total direct costs for the SD/FF unit were estimated on the basis of the cost equation:

$$C = 7.115\ Q^{0.517}$$

where:

C = total direct cost, \$x10^3 in December 1987
Q = volumetric flow, acfm

This cost equation is based on comprehensive information collected by EPA as a part of the municipal waste combustion study. Vendors contacted during this study indicated that these costs would provide reasonable ±30 percent estimates.

4.3.4 HEPA Filter Cost Assumptions

Calciner gas stream characteristics that affect HEPA filter design and costs are moisture content, inorganic acid content, and loading in the gas stream to be treated. A spray tower is assumed to exist upstream of the HEPA filtration system; the high moisture content of the spray tower exit gases requires treatment of the gases by a demister and reheater upstream of the HEPA filter. These components were included in the cost of the HEPA system. Because the exhaust gases are corrosive, Type 304 stainless steel housings and filter frames, acid-corrosion resistant filter media, and vinyl-clad aluminum separators are included in the cost of the system and replacement filters to provide the best available corrosion resistance. Because the PM loading in the gas stream exceeds the recommended maximum of 2.3 mg/m^3 (0.001 gr/acf), the cost of a prefiltration system is included in the total system cost. Estimated costs of the HEPA system, consisting of the prefilters, HEPA filters, prefilter/HEPA filter bank housing, demister, reheater, and demister/reheater housing were obtained from equipment vendors.

A major operating cost for HEPA filters is filter replacement. The operating life of a HEPA depends on the increase in pressure drop resulting from particle collection within the filter media. A general guideline used to design filter systems is 4 lb/1,000 ft^3/min rated capacity (1.82 kg/1,000 ft^3/min).[12] Filter life was estimated by assuming a HEPA capacity of 7.9 lb/1,000 ft^3/min (3.6 kg/1,000 ft^3/min) per filter based on vendor information.[21] The methodology used to estimate filter life consisted of the following steps:

1. Obtain particle size distribution in spray tower exit gas stream from test data (where available);
2. Predict the mass of particles removed by prefiltration using design prefilter removal efficiencies for a given particle size;
3. Predict mass of particles removed by HEPA filter using filter design HEPA removal efficiencies;
4. Assume a filter capacity for HEPA filter and calculate HEPA filter operating life with and without use of a prefilter;
5. Calculate prefilter life as two times the HEPA filter life without the use of a prefilter; and
6. Calculate HEPA filter life as the HEPA capacity divided by the particulate loading rate into the HEPA filter.

Estimation of the labor cost to replace prefilters and HEPA filters as they are exhausted is based on 0.25 hours of labor per filter per replacement cycle. For example, filter replacement for a 36 filter bank requires 9 hours.

Exhausted filters are expected to exhibit increased concentrations of particulate matter containing Po-210 and Pb-210. To reduce the risk of inhalation of particles that may become airborne as a result of filter handling during the replacement process, an automatic bagout containment system is included in the system cost. Automatic bagout facilitates removal of exhausted filters without direct operator contact. Heavy duty PVC bags are installed inside the filter housing between the filters and the housing access door. When the door is opened, the bags form a barrier between the operator and the contaminated filter. By working through the bag, the operator can remove the filter and draw it into the bag without direct contact. The cost of replacement bags was included in the estimate of replacement material cost.

4.4 REFERENCES FOR SECTION 4

1. Joseph, G., and D. Beachler, APTI Course SI:412C Wet Scrubber Plan Review. U. S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. EPA 450/2-82-020. March 1984.

2. Memo and attachments from Wallace, D. and K. Leeds, Midwest Research Institute, to Beck, L., EPA/ISB. August 9, 1988. Site Visit--Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho.

3. Memo and attachments from Wallace, D. and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 23, 1988. Site Visit--Stauffer Elemental Phosphorus Plant, Mount Pleasant, Tennessee.

4. Schifftner, K. and H. Hesketh. Wet Scrubbers, A Practical Handbook. Chelsea, Lewis Publishers, Inc. 1986.

5. U. S. Environmental Protection Agency. Control Techniques for Particulate Emissions from Stationary Sources--Volume I. Publication No. EPA-450/3-81-005a. Research Triangle Park, N.C. September 1982.

6. Reference was eliminated to prevent disclosure of CBI data.

7. Memo and attachments from Wallace, D. and J. Obremski, Midwest Research Institute, to Beck, L., EPA/ISB. August 9, 1988. Site Visit--Stauffer Elemental Phosphorus Plant, Silver Bow, Montana.

8. U. S. Environmental Protection Agency. Operation and Maintenance Manual for Electrostatic Precipitators. Publication No. EPA/625-1-85/017. Research Triangle Park, N.C. September 1985.

9. Beachler, D., APTI Course SI:412B, Electrostatic Precipitator Plan Review. Prepared for U. S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. EPA 450/2-82-019. July 1983.

10. Sedman, C. and T. Brna. Municipal Waste Combustion Study: Flue Gas Cleaning Technology. Prepared for U. S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. EPA 530-SW-87-021d. June 1987.

11. Beachler, D., APTI Course SI:412A, Baghouse Plan Review. Prepared for U. S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. EPA 450/2-82-005. April 1982.

12. Burchsted, C. A., Fuller, A. B., and Kahn, J. E. Nuclear Air Cleaning Handbook. Oak Ridge National Laboratory, Oak Ridge, Tennessee. ERDA Publication No. 76-21. 1976.

13. Radian Corporation. Draft Final Emission Test Report. Monsanto Elemental Phosphorus Plant, Soda Springs, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

14. Radian Corporation. Draft Final Emission Test Report. FMC Elemental Phosphorus Plant, Pocatello, Idaho. Prepared for U. S. Environmental Protection Agency under Contract No. 68-02-4338. Research Triangle Park, North Carolina. October 1988.

15. Hesketh, H. Air Pollution Control. Ann Arbor, Ann Arbor Science. 1981.

16. Environment Canada. The National Incinerator Testing and Education Program: Air Pollution Control Technology, Report EPS 3/UP/2. Ottawa, Ontario. September 1986.

17. GARD, Inc. Capital and Operating Costs of Selected Air Pollution Control Systems. Prepared for U. S. Environmental Protection Agency. Research Triangle Park, N.C. Publication No. EPA 450/5-80-002. December 1978.

18. U. S. Environmental Protection Agency. EAB Control Cost Manual, Third Edition. Publication No. EPA 450/5-87-001A. Research Triangle Park, N.C. February 1987.

19. Turner, J. H. et al. Sizing and Costing of Electrostatic Precipitators. Part I. Sizing Considerations. Journal of the Air Pollution Control Association. 38(4):458-421.

20. Turner, J. H. et al. Sizing and Costing of Electrostatic Precipitators. Part II. Costing Considerations. Journal of the Air Pollution Control Association. 38(5):715-726.

21. Telecon. Allen, K., Midwest Research Institute, with Clark, R., Environmental Product Sales, Inc., Raleigh, N.C. August 12, 1988.

5.0 CONTROL ALTERNATIVE PERFORMANCE AND COST

Information on the feasibility, performance, and costs of alternative emission control techniques for elemental phosphorus process calciners and nodulizing kilns is needed to assess potential regulatory limits for Po-210 and Pb-210 emissions. This section defines viable control alternatives and presents information on the performance and capital and annualized costs of those alternatives for each of the five operating facilities. Nationwide reductions in Po-210 and Pb-210 emissions also are estimated, and total nationwide capital and annualized cost estimates are presented. The results presented in this section are based on the emission data presented in Section 3.0 and the performance and cost estimation procedures presented in Section 4.0 for different control technologies.

5.1 DEFINITION OF CONTROL ALTERNATIVES

As outlined in Section 4, four fine PM control techniques were identified as having potential for control of Po-210 and Pb-210 emissions from calciners--venturi scrubbers, wet electrostatic precipitators (ESP's), spray dryers with pulse jet fabric filters (SD/FF's) and high energy particulate air (HEPA) filters. Ten different control alternatives based on these four technologies were examined. Four of the alternatives are based on venturi scrubbers at different pressure drops (ΔP's), four are based on wet ESP's with different specific collecting areas (SCA's), and one each is based on a SD/FF system and a HEPA filter system. The paragraphs below describe the control alternatives and the assumptions that were used to assess performance and cost of these systems.

Four of the control alternatives comprise venturi scrubbers operated downstream from a spray tower. Four different pressure drops were examined--2.5 kPa (10 in. w.c.), 6.2 kPa (25 in. w.c.), 10 kPa (40 in. w.c.), and 20 kPa (80 in. w.c.). The values from 2.5 kPa to 10 kPa represent the range of ΔP's for venturi scrubbers at recently installed control systems on elemental phosphorus plant calcining operations. The 20 kPa level was selected as a control alternative that is more stringent than the controls typically used in the industry, but that has been applied to other metallurgical processing facilities. Two other assumptions were made in evaluating the performance and costs of the venturi scrubber control alternatives. First, a spray tower was assumed to be used upstream from the venturi to control acid gases and condition the gas stream for the venturi. All of the operating facilities except FMC currently have a spray tower as a part of their control system that is assumed to be useable as the conditioning system for the venturi. Second, for all the venturi scrubber control alternatives, the L/G ratio was assumed to be 1.3 ℓ/m^3 (10 gal/1,000 ft^3). This value was selected because it represents the upper end of the range typically found in venturi scrubber applications. A cyclonic mist eliminator also was assumed for all venturi scrubber alternatives. Note that although FMC does not have a spray tower in their systems, no tower was costed for this study. The low energy scrubber that FMC has in place as assumed to provide coarse PM control and gas conditioning.

The four ESP control alternatives that were considered comprised spray towers for acid gas control and gas stream conditioning followed by flat-plate wet ESP's. The four SCA levels that were considered were 39.4 $(m/s)^{-1}$ (200 ft^2/kacfm), 78.8 $(m/s)^{-1}$ (400 ft^2/kacfm), 118 $(m/s)^{-1}$ (600 ft^2/kacfm), and 158 $(m/s)^{-1}$ (800 ft^2/kacfm). These four SCA levels are higher than the SCA at the one wet ESP that is applied to a nodulizing kiln. However, that unit is an older unit with relatively low PM removal efficiency. The range of 39.4 to 158 $(m/s)^{-1}$ (220 to 800 ft^3/kacfm) is representative of the SCA levels typically found on metallurgical and mineral processing facilities. The spray tower upstream from the ESP will remove acid gases from the gas stream and reduce the temperature to 65° to 70°C (150° to 160°F) to assure that the Po-210 and Pb-210 are condensed before they enter the ESP.

The ninth control alternative is the SD/FF control system described in Section 4.1.4. For this alternative, the exhaust stream is vented directly to the spray dryer without pretreatment. No SD/FF systems have been applied to elemental phosphorus facilities. However, they were selected as a stringent control technique because they have been demonstrated to control acid gases and condensation PM in other metallurgical and mineral processing operations such as aluminum reduction and glass manufacturing. Key assumptions that were made to estimate performance and cost are that sufficient moisture will be added to reduce gas temperature to 120°C (250°F) at the inlet to the FF, that lime will be added at a 1.5 stoichiometric ratio for HF and SO_2 combined, and that a pulse jet fabric filter capable of maintaining an outlet grain loading of 0.023 g/dscm (0.01 gr/dscf) will be installed.

The final control alternative comprises a spray tower scrubber, a reheat system, a prefilter, and a HEPA filter in sequence. The spray tower is used to reduce the acid content of the gas stream and to remove larger sized PM. The reheat system is needed to raise the gas stream temperature sufficiently to prevent condensation of moisture and inorganic acids in the HEPA filter. The prefilter is used to reduce the PM loading to the HEPA filter and thereby extend its life. The HEPA filter system has not been applied to elemental phosphorus facilities and generally is not applied to furnaces that generate gas volumes as large as those generated by elemental phosphorus process calciners or nodulizing kilns. However, the system was selected for consideration because HEPA filters have been used successfully to control radionuclide emissions from uranium processing facilities and they do provide a much greater level of control than is provided by the other control alternatives.

5.2 PERFORMANCE OF CONTROL ALTERNATIVES

The performance of each of the 10 control alternatives was calculated based on the reduction from baseline emissions that could be achieved by application of the control alternative. For each control alternative and each operating facility, annual emissions of Po-210 and Pb-210 were estimated using the procedures described in Section 4. These estimated emission levels were compared to the baseline emission estimates that are presented in Table 3-9 to determine achievable emission reductions.

Performance models for venturi scrubbers and wet ESP's are presented in Sections 4.2.1 and 4.2.2, respectively. Application of these models requires information on the emission rate of Po-210 and Pb-210 at the venturi and ESP inlet and on the particle size distribution of these emissions. The estimates of Po-210 and Pb-210 emission rates at the scrubber/ESP inlet, based on the assumptions that a spray tower is located upstream from primary control device are:

Facility	Emissions, Ci/yr Po-210	 Pb-210
FMC	10	0.14
Monsanto	30	9.5
Stauffer, Montana	2.4	0.32
Stauffer, Tennessee	0.28	0.058
Occidental	0.31	0.064

The estimates for FMC, Monsanto, and Stauffer, Montana, are based on tests conducted by EPA in 1983 and 1988 that measured emissions at the outlet of low-energy scrubbers at those facilities.[1-3] Because the control systems at the two Tennessee plants consist of spray tower scrubbers, the emission estimates for those two facilities are based on the baseline emissions from those facilities that were presented in Table 3-9. Estimates of the particle size distribution for these emissions are presented in Table 5-1. Separate estimates were developed for moving grate calciners (FMC) and rotary kilns (all other facilities).

The performance models presented in Chapter 4 and available test data were used to develop estimates of the fractional efficiencies that could be achieved by the venturi scrubber and wet ESP control alternatives for the six particle size fractions identified in Table 5-1. The results of the model calculations are presented in Table 5-2 for the four venturi scrubber alternatives and in Table 5-3 for wet ESP's. Generally, the models indicated that all of the control measures are relatively effective in removing particles greater than 1 μm in diameter. However, only the high efficiency systems (venturi scrubbers with ΔP's of 10 kPa or greater and wet ESP's with an SCA of 78.8 $(m/s)^{-1}$) are effective in controlling particles less than 1 μm in diameter, which is the size fraction in which the Po-210 and Pb-210 are concentrated.

Because the model results and test results agreed well for wet ESP's, the fractional efficiencies presented in Table 5-3, the particle size distributions presented in Table 5-1, and the estimated annual inlet emission rates presented above were used directly to estimate annual Po-210 and Pb-210 emission rates.

TABLE 5-1. PARTICLE SIZE DISTRIBUTIONS FOR Po-210 AND Pb-210[a]

Particle size, µm		Po-210		Pb-210	
Range	Median	Moving grate[b]	Rotary kiln[c]	Moving grate[b]	Rotary kiln[c]
<0.5	3.5	76.0	52.2	36.5	60.0
0.5-0.9	0.67	4.0	21.6	17.7	18.1
0.9-1.5	1.16	3.8	12.9	11.5	14.3
1.5-3	2.12	2.8	8.9	8.8	5.2
3-10	5.48	3.7	3.4	13.2	2.0
>10	14	9.6	1.0	12.3	0.4

[a] Assumed to be at the outlet to a spray tower upstream from the high-efficiency PM collector.

[b] Based on size distribution at the FMC slinger scrubber outlet.

[c] Based on size distribution at outlet from spray tower at Stauffer.

TABLE 5-2. ESTIMATED FRACTIONAL EFFICIENCIES FOR VENTURI SCRUBBER CONTROL ALTERNATIVES

Particle size, μm		Fractional efficiencies			
Range	Median	ΔP (kPa) = 2.5	6.2	10	20
<0.5	3.5	10.0	31.2	46.9	69.9
0.5-0.9	0.67	49.9	80.6	89.7	96.5
0.9-1.5	1.16	86.5	96.8	98.5	99.5
1.5-3	2.12	98.1	99.5	99.8	99.9
3-10	5.48	99.8	99.9	>99.9	>99.9
>10	14	>99.9	>99.9	>99.9	>99.9

TABLE 5-3. ESTIMATED FRACTIONAL EFFICIENCIES FOR WET ESP CONTROL ALTERNATIVES

Particle size, µm		Fractional efficiencies			
Range	Median	SCA (m/s^{-1}) = 39.4	78.8	118	158
<0.5	3.5	63.4	86.6	95.1	98.2
0.5-0.9	0.67	80.2	96.1	99.2	99.8
0.9-1.5	1.16	92.3	99.4	99.9	>99.9
1.5-3	2.12	98.8	>99.9	>99.9	>99.9
3-10	5.48	>99.9	>99.9	>99.9	>99.9
>10	14	>99.9	>99.9	>99.9	>99.9

As discussed in Section 4.3, the measured efficiencies for Po-210 and Pb-210 at Monsanto were significantly higher than the efficiencies estimated by the scrubber model. Consequently, the estimated scrubber efficiencies estimated by the model were adjusted to compensate for the apparent low bias of the model. Table 5-4 presents the estimates of scrubber performance for the four control alternatives for Po-210 and Pb-210 for rotary kiln and moving grate calciners. The left half of this table presents the modeled results based on the data presented in Tables 5-1 and 5-2. The right half of the table presents the adjusted results. The basis for these adjusted results and the calculation procedures are documented in Reference 4.

The adjusted efficiencies presented in Table 5-4 were applied to the emission rates presented above to estimate controlled emissions under each of the four venturi scrubber options. The results are presented in Tables 5-5 and 5-6. These emission rates presented in Tables 5-5 and 5-6 were compared to the baseline emission rates presented in Table 3-7, and emission reductions were calculated. These results are presented in Table 5-7 for Po-210 and 5-8 for Pb-210.

Control efficiencies also were developed for the SD/FF and the HEPA using the procedures described in Section 4.2. Efficiencies for the SD/FF system were calculated based on an assumed outlet loading of 0.023 g/dscm (0.01 gr/dscf) and estimated inlet loadings of 13 g/dscm (5.7 gr/dscf) for rotary kilns and 15 g/dscm (6.7 gr/dscf) for moving grate calciners. These inlet loading estimates are based on the uncontrolled PM emission rates measured at FMC and Stauffer in 1984 and the quantity of lime added to the system to control SO_2 at concentrations of 500 ppmv and HF at 1,500 ppmv.[1,3] The resultant efficiencies are 99.82 percent for rotary kilns and 99.85 percent for moving grates. For the HEPA filter, the efficiency was assumed to be 99.998 percent as described in Section 4.2.4.

The estimated efficiencies defined above then were used to estimate Po-210 and Pb-210 emissions for each of the five operating facilities. Since the HEPA filter is installed downstream from a spray tower, the emission rates presented above were used as "uncontrolled" emission rates. The SD/FF system does not include a spray tower. Consequently, "uncontrolled" emissions were estimated using the spray tower outlet rates defined above and the assumption that the spray tower is almost 65 percent

TABLE 5-5. ESTIMATED Po-210 EMISSION LEVELS ACHIEVED BY CONTROL ALTERNATIVES

Control alternative	Emission levels, Ci/yr				
			Stauffer		
	FMC	Monsanto	Montana	Tennessee	Occidental
Wet scrubber					
ΔP = 2.5 kPa	8.0	21	1.5	0.20	0.22
ΔP = 6.2 kPa	4.0	14	1.1	0.13	0.14
ΔP = 10 kPa	2.0	3.0	0.24	0.028	0.031
ΔP = 20 kPa	1.0	1.5	0.12	0.014	0.016
ESP					
SCA = 39.4 $(m/s)^{-1}$	2.9	7.4	0.59	0.07	0.08
SCA = 78.8 $(m/s)^{-1}$	1.0	2.4	0.19	0.02	0.02
SCA = 118 $(m/s)^{-1}$	0.38	0.84	0.07	0.01	0.01
SCA = 158 $(m/s)^{-1}$	0.14	0.29	0.02	<0.01	<0.01
Spray dryer/fabric filter	0.043	0.15	0.012	0.001	0.002
HEPA filter	<0.001	<0.001	<0.001	<0.001	<0.001

TABLE 5-6. ESTIMATED Pb-210 EMISSION LEVELS ACHIEVED BY CONTROL ALTERNATIVES

Control alternative	Emission levels, mCi/yr				
			Stauffer		
	FMC	Monsanto	Montana	Tennessee	Occidental
Wet scrubber					
ΔP = 2.5 kPa	70	6,600	220	41	45
ΔP = 6.2 kPa	28	2,800	96	17	19
ΔP = 10 kPa	9.8	950	32	5.8	6.4
ΔP = 20 kPa	5.6	480	16	2.9	3.2
ESP					
SCA = 39.4 $(m/s)^{-1}$	25	2,500	85	15	17
SCA = 78.8 $(m/s)^{-1}$	8.0	840	2.8	5.1	5.6
SCA = 118 $(m/s)^{-1}$	2.8	290	9.6	1.7	1.9
SCA = 158 $(m/s)^{-1}$	1.0	100	3.5	0.64	0.70
Spray dryer/fabric filter	0.6	49	1.6	0.29	0.32
HEPA filter	0.003	0.019	<0.01	<0.01	<0.01

TABLE 5-7. REDUCTION OF Po-210 EMISSIONS FROM BASELINE

Control alternative	Emission reduction, Ci/yr					
			Stauffer			
	FMC	Monsanto	Montana	Tennessee	Occidental	Total
Wet scrubber						
ΔP = 2.5 kPa	2.0	[a]	[a]	0.08	0.09	2.2
ΔP = 6.2 kPa	6.0	[a]	[a]	0.15	0.17	6.3
ΔP = 10 kPa	8.0	[a]	0.5	0.25	0.28	9.0
ΔP = 20 kPa	9.0	[a]	0.62	0.27	0.29	10.2
ESP						
SCA = 39.4 $(m/s)^{-1}$	7.1	[a]	0.15	0.21	0.23	7.7
SCA = 78.8 $(m/s)^{-1}$	9.0	[a]	0.55	0.26	0.29	10.1
SCA = 118 $(m/s)^{-1}$	9.6	0.56	0.67	0.29	0.30	11.4
SCA = 158 $(m/s)^{-1}$	9.9	1.1	0.72	0.28	0.31	12.3
SD/FF	10	1.2	0.73	0.28	0.31	12.5
HEPA	10	1.4	0.74	0.28	0.31	12.7

[a] Baseline control results in lower emissions than those achievable by this control alternative.

TABLE 5-8. REDUCTION OF Pb-210 EMISSIONS FROM BASELINE

	Emission reduction, mCi/yr					
			Stauffer			
Control alternative	FMC	Monsanto	Montana	Tennessee	Occidental	Total
Wet scrubber						
ΔP = 2.5 kPa	70	a	a	17	19	110
ΔP = 6.2 kPa	110	a	14	41	45	210
ΔP = 10 kPa	130	a	78	52	58	320
ΔP = 20 kPa	130	a	94	55	61	340
ESP						
SCA = 39.4 $(m/s)^{-1}$	120	a	25	43	47	240
SCA = 78.8 $(m/s)^{-1}$	130	a	82	53	58	320
SCA = 118 $(m/s)^{-1}$	140	50	100	56	62	410
SCA = 158 $(m/s)^{-1}$	140	240	110	57	63	610
SD/FF	140	290	110	58	64	660
HEPA	140	340	110	58	64	710

[a] Baseline control results in lower emissions than those achievable by this control option.

efficient in removing Po-210 and Pb-210 from the exhaust stream. This 65 percent efficiency estimate is based on the performance measured by EPA at Stauffer.[3] The resulting emission estimates are presented in Tables 5-5 and 5-6 for Po-210 and Pb-210, respectively. The reductions from baseline are presented in Tables 5-7 and 5-8. Both of these control alternatives achieve a significant reduction in emissions beyond those that are estimated for venturi scrubbers and wet ESP's.

5.3 COSTS OF CONTROL ALTERNATIVES

Capital and annualized costs for each of the 10 control alternatives evaluated were developed using the procedures described in Section 4.3. Nationwide and plant specific capital and annualized cost summaries for each control alternative are presented in Tables 5-9 and 5-10, respectively. Nationwide capital and annualized costs for the 10 control alternatives are compared graphically in Figures 5-1 and 5-2. A more detailed breakdown of costs for each alternative is presented in Tables 5-11 through 5-20. Details on the cost inputs for the venturi scrubber, wet wall ESP, SD/FF, and HEPA filter system for each facility are presented in Appendices A through E.

TABLE 5-9. CAPITAL COST OF CONTROL ALTERNATIVES
(Rounded Cost, 1988 $)

Control	Plant					Total
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee	
1. Venturi scrubber						
10 inch ΔP	5,940,000	a	2,020,000	a	1,460,000	9,400,000
25 inch ΔP	7,810,000	a	2,510,000	1,690,000	1,870,000	13,000,000
40 inch ΔP	8,500,000	a	3,230,000	1,890,000	2,460,000	16,000,000
80 inch ΔP	13,280,000	6,590,000	6,120,000	3,870,000	5,230,000	35,000,000
2. Electrostatic precipitator						
200 SCA	10,640,000	6,630,000	4,530,000	2,350,000	3,140,000	27,000,000
400 SCA	15,500,000	9,860,000	6,500,000	3,310,000	4,390,000	40,000,000
600 SCA	20,280,000	12,890,000	8,600,000	4,080,000	5,950,000	52,000,000
800 SCA	24,790,000	15,720,000	11,340,000	4,750,000	7,390,000	64,000,000
3. Spray dryer/ fabric filter	17,330,000	10,380,000	10,060,000	7,540,000	6,580,000	52,000,000
4. HEPA filtration	4,200,000	2,870,000	1,610,000	620,000	1,020,000	10,000,000

[a] No costs are incurred for this alternative because facility has more efficient control in place.

TABLE 5-10. ANNUALIZED COST OF CONTROL ALTERNATIVES (Rounded Cost, 1988 $)

	Plant					
Control	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee	Total
1. Venturi scrubber						
10 inch ΔP	1,600,000	a	740,000	a	590,000	2,900,000
25 inch ΔP	2,110,000	a	920,000	680,000	750,000	4,500,000
40 inch ΔP	2,430,000	a	1,150,000	740,000	930,000	5,200,000
80 inch ΔP	3,750,000	2,220,000	1,910,000	1,110,000	1,610,000	11,000,000
2. Electrostatic precipitator						
200 SCA	2,010,000	1,260,000	970,000	790,000	640,000	5,700,000
400 SCA	2,840,000	1,820,000	1,320,000	830,000	850,000	7,700,000
600 SCA	3,650,000	2,330,000	1,670,000	870,000	1,120,000	9,600,000
800 SCA	4,430,000	2,820,000	2,030,000	910,000	1,370,000	12,000,000
3. Spray dryer/fabric filter	9,700,000	5,430,000	4,630,000	3,070,000	3,120,000	26,000,000
4. HEPA filtration	10,140,000	15,700,000	10,070,000	2,960,000	7,450,000	47,000,000

[a] No costs are incurred for this alternative because facility has more efficient control in place.

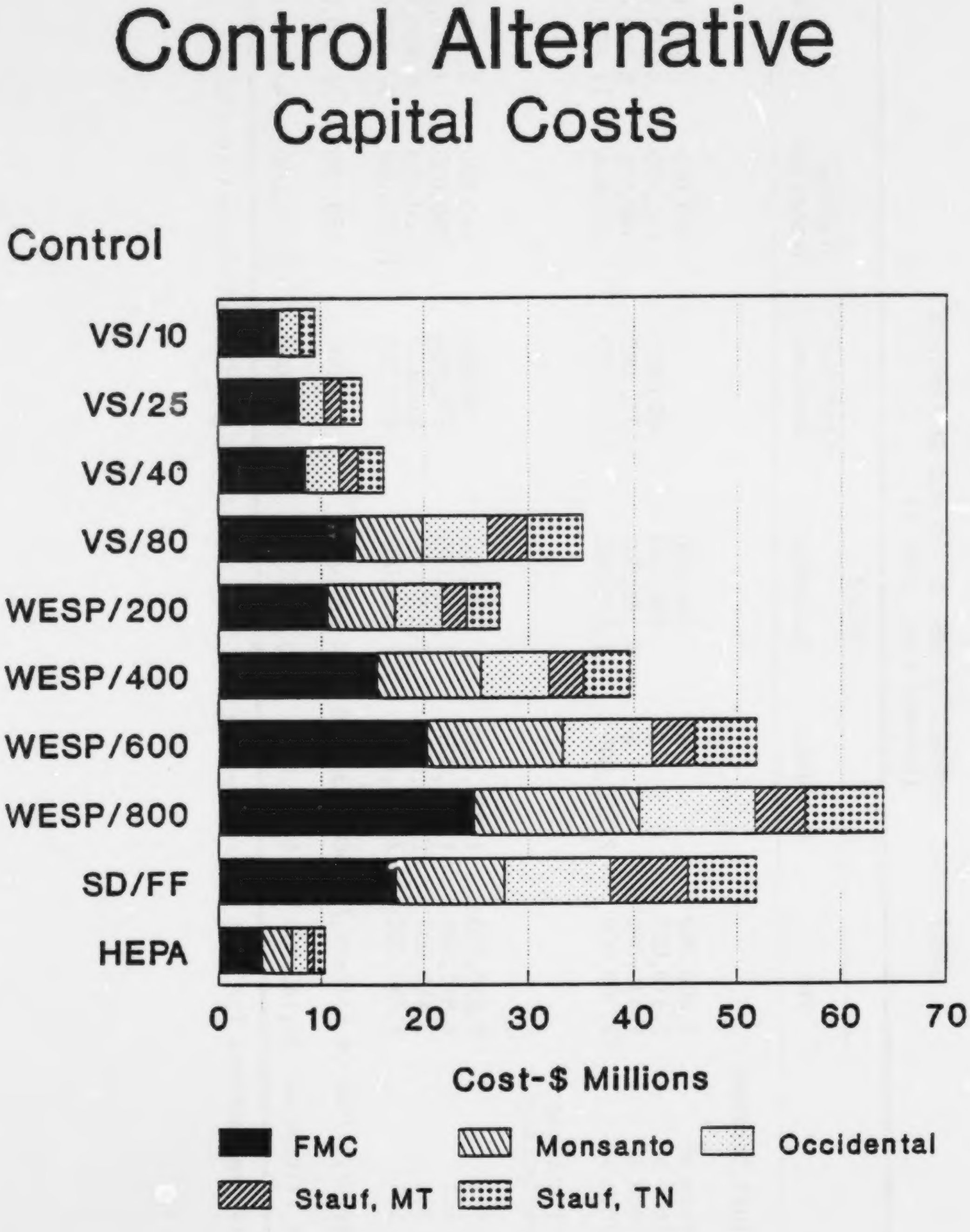

Figure 5-1. Capital costs of control alternatives.

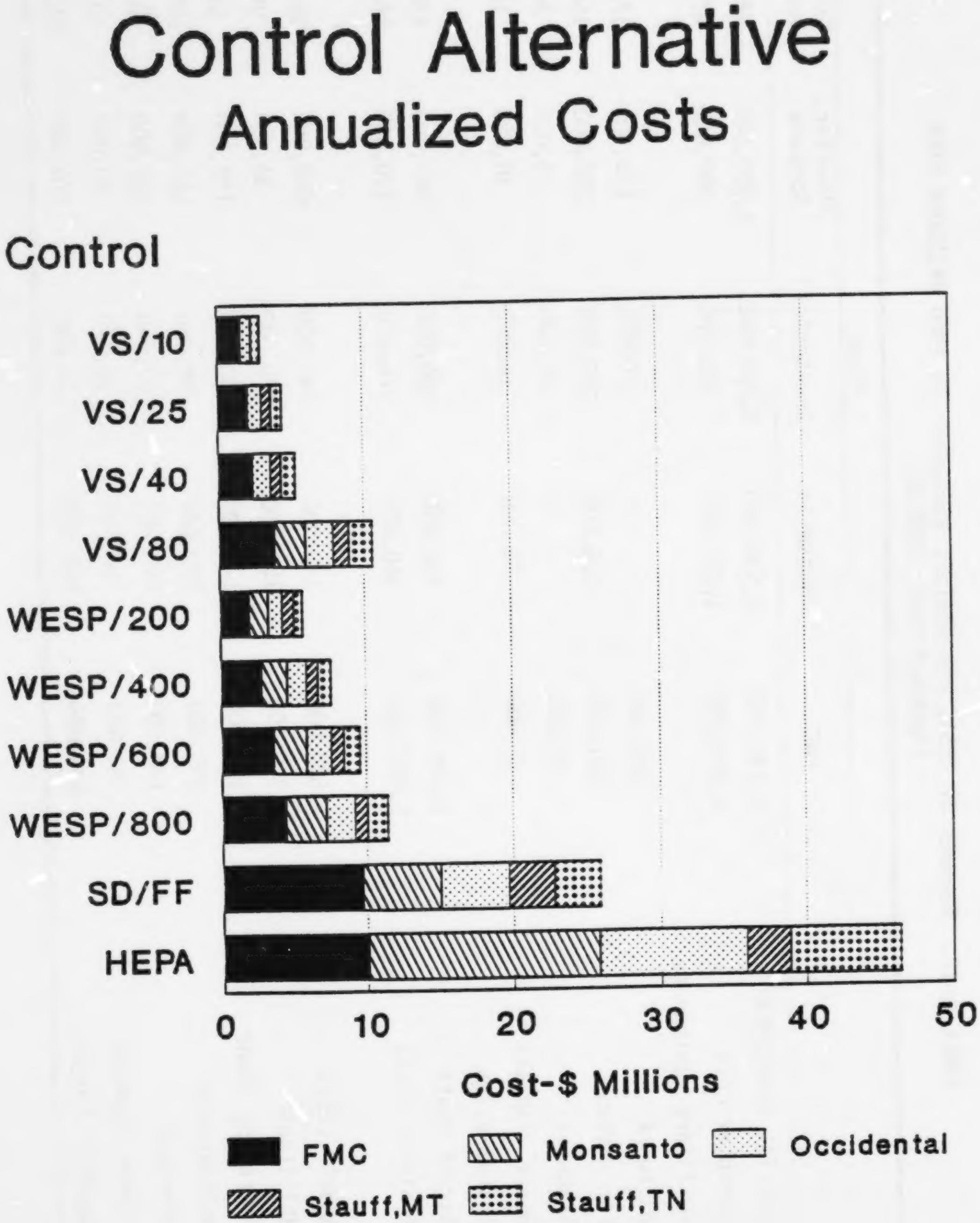

Figure 5-2. Annualized costs of control alternatives.

TABLE 5-11. SUMMARY OF COSTS FOR VENTURI SCRUBBER--10 INCH PRESSURE DROP
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	5,940,000	2,530,000	2,020,000	1,690,000	1,460,000
1. Scrubber cost	1,580,000	1,000,000	650,000	390,000	470,000
2. Auxiliary equipment					
Ductwork	960,000	--	170,000	170,000	120,000
Fan system	500,000	310,000	210,000	290,000	150,000
Stack(s)	50,000	--	20,000	20,000	20,000
Waste disposal	19,000	20,000	10,000	10,000	10,000
3. Installation					
Direct costs	1,740,000	740,000	590,000	500,000	430,000
Indirect costs	1,090,000	460,000	370,000	310,000	266,000
TOTAL ANNUAL COSTS	1,600,000	970,000	740,000	660,000	590,000
1. Utilities	240,000	150,000	120,000	30,000	90,000
2. Operating labor	120,000	120,000	90,000	120,000	60,000
3. Maintenance	100,000	100,000	80,000	100,000	100,000
4. Overhead	140,000	140,000	100,000	140,000	90,000
5. Sludge disposal	60,000	60,000	30,000	10,000	20,000
6. Capital charges	940,000	400,000	320,000	270,000	230,000

TABLE 5-12. SUMMARY OF COSTS FOR VENTURI SCRUBBER--25 INCH PRESSURE DROP
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	7,810,000	3,200,000	2,510,000	1,690,000	1,870,000
1. Scrubber cost	2,080,000	1,180,000	770,000	390,000	560,000
2. Auxiliary equipment					
Ductwork	1,270,000	--	230,000	170,000	160,000
Fan system	670,000	470,000	270,000	290,000	230,000
Stack(s)	50,000	--	20,000	20,000	20,000
Waste disposal	19,000	20,000	10,000	10,000	10,000
3. Installation					
Direct costs	2,290,000	940,000	740,000	500,000	550,000
Indirect costs	1,430,000	590,000	460,000	310,000	340,000
TOTAL ANNUAL COSTS	2,110,000	1,200,000	920,000	680,000	750,000
1. Utilities	450,000	280,000	230,000	50,000	180,000
2. Operating labor	120,000	120,000	90,000	120,000	60,000
3. Maintenance	100,000	100,000	80,000	100,000	100,000
4. Overhead	140,000	140,000	100,000	140,000	90,000
5. Sludge disposal	70,000	60,000	30,000	10,000	20,000
6. Capital charges	1,230,000	500,000	400,000	270,000	290,000

TABLE 5-13. SUMMARY OF COSTS FOR VENTURI SCRUBBER--40 INCH PRESSURE DROP
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	8,500,000	4,460,000	3,230,000	1,890,000	2,460,000
1. Scrubber cost	2,080,000	1,550,000	950,000	390,000	730,000
2. Auxiliary equipment					
Ductwork	1,270,000	--	290,000	170,000	210,000
Fan system	1,030,000	760,000	410,000	390,000	310,000
Stack(s)	50,000	--	20,000	20,000	20,000
Waste disposal	20,000	20,000	10,000	10,000	10,000
3. Installation					
Direct costs	2,490,000	1,310,000	950,000	550,000	720,000
Indirect costs	1,560,000	820,000	590,000	350,000	450,000
TOTAL ANNUAL COSTS	2,430,000	1,530,000	1,150,000	740,000	930,000
1. Utilities	660,000	410,000	340,000	70,000	270,000
2. Operating labor	120,000	120,000	90,000	120,000	60,000
3. Maintenance	100,000	100,000	80,000	100,000	100,000
4. Overhead	140,000	140,000	100,000	140,000	90,000
5. Sludge disposal	70,000	60,000	30,000	10,000	20,000
6. Capital charges	1,340,000	1,700,000	510,000	300,000	390,000

TABLE 5-14. SUMMARY OF COSTS FOR VENTURI SCRUBBER--80 INCH PRESSURE DROP
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	13,280,000	6,590,000	6,120,000	3,870,000	5,230,000
1. Scrubber cost	2,970,000	2,220,000	1,940,000	460,000	1,610,000
2. Auxiliary equipment					
Ductwork	1,800,000	--	400,000	220,000	300,000
Fan system	2,110,000	1,210,000	820,000	1,300,000	800,000
Stack(s)	50,000	--	20,000	20,000	20,000
Waste disposal	20,000	20,000	10,000	10,000	10,000
3. Installation					
Direct costs	3,890,000	1,930,000	1,790,000	1,130,000	1,530,000
Indirect costs	2,430,000	1,210,000	1,120,000	710,000	960,000
TOTAL ANNUAL COSTS	3,750,000	2,220,000	1,910,000	1,110,000	1,610,000
1. Utilities	1,230,000	760,000	640,000	130,000	510,000
2. Operating labor	120,000	120,000	90,000	120,000	60,000
3. Maintenance	100,000	100,000	80,000	100,000	100,000
4. Overhead	140,000	140,000	100,000	140,000	90,000
5. Sludge disposal	70,000	60,000	30,000	10,000	20,000
6. Capital charges	2,090,000	1,040,000	960,000	610,000	820,000

TABLE 5-15. SUMMARY OF COSTS FOR WET WALL ELECTROSTATIC PRECIPITATOR--200 SCA
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	10,640,000	6,630,000	4,530,000	2,350,000	3,140,000
1. Purchased equipment	2,650,000	1,540,000	1,390,000	660,000	950,000
2. Auxiliary equipment					
Ductwork	1,010,000	780,000	180,000	80,000	130,000
Fan system	330,000	190,000	150,000	140,000	110,000
Stack(s)	40,000	--	--	--	--
3. Installation					
Direct costs	3,910,000	2,430,000	1,660,000	860,000	1,150,000
Indirect costs	2,710,000	1,690,000	1,150,000	600,000	800,000
TOTAL ANNUAL COSTS	2,010,000	1,260,000	970,000	790,000	640,000
1. Direct costs	270,000	180,000	170,000	100,000	120,000
2. Indirect costs	1,740,000	1,080,000	800,000	690,000	520,000

TABLE 5-16. SUMMARY OF COSTS FOR WET WALL ELECTROSTATIC PRECIPITATOR--400 SCA
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	15,500,300	9,860,000	6,500,000	3,310,000	4,390,000
1. Purchased equipment	4,490,000	2,760,000	2,130,000	1,030,000	1,420,000
2. Auxiliary equipment					
Ductwork	1,010,000	780,000	180,000	80,000	130,000
Fan system	330,000	190,000	150,000	140,000	110,000
Stack(s)	40,000	--	--	--	--
3. Installation					
Direct costs	5,700,000	3,620,000	2,390,000	1,210,000	1,610,000
Indirect costs	3,950,000	2,510,000	1,650,000	840,000	1,120,000
TOTAL ANNUAL COSTS	2,840,000	1,820,000	1,320,000	830,000	850,000
1. Direct costs	320,000	220,000	200,000	100,000	130,000
2. Indirect costs	2,520,000	1,600,000	1,120,000	730,000	720,000

TABLE 5-17. SUMMARY OF COSTS FOR WET WALL ELECTROSTATIC PRECIPITATOR--600 SCA
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	20,280,000	12,890,000	8,600,000	4,080,000	5,950,000
1. Purchased equipment	6,290,000	3,910,000	2,930,000	1,320,000	2,010,000
2. Auxiliary equipment					
Ductwork	1,010,000	780,000	180,000	80,000	130,000
Fan system	330,000	190,000	150,000	140,000	110,000
Stack(s)	40,000	--	--	--	--
3. Installation					
Direct costs	7,450,000	4,730,000	3,160,000	1,500,000	2,180,000
Indirect costs	5,160,000	3,280,000	2,190,000	1,040,000	1,510,000
TOTAL ANNUAL COSTS	3,650,000	2,330,000	1,670,000	870,000	1,120,000
1. Direct costs	370,000	250,000	220,000	110,000	150,000
2. Indirect costs	3,280,000	2,080,000	1,450,000	760,000	970,000

TABLE 5-18. SUMMARY OF COSTS FOR WET WALL ELECTROSTATIC PRECIPITATOR--800 SCA
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	24,790,000	15,720,000	11,340,000	4,750,000	7,390,000
1. Purchased equipment	8,000,000	4,980,000	4,410,000	1,570,000	2,560,000
2. Auxiliary equipment					
Ductwork	1,010,000	780,000	180,000	80,000	130,000
Fan system	330,000	190,000	150,000	140,000	110,000
Stack(s)	40,000	--	--	--	--
3. Installation					
Direct costs	9,100,000	5,770,000	3,900,000	1,740,000	2,710,000
Indirect costs	6,310,000	4,000,000	2,700,000	1,210,000	1,880,000
TOTAL ANNUAL COSTS	4,430,000	2,820,000	2,030,000	910,000	1,370,000
1. Direct costs	420,000	280,000	250,000	120,000	170,000
2. Indirect costs	4,010,000	2,540,000	1,780,000	790,000	1,200,000

TABLE 5-19. SUMMARY OF COSTS FOR SPRAY DRYER/FABRIC FILTER
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	17,330,000	10,380,000	10,060,000	7,540,000	6,580,000
1. Purchased equipment	10,870,000	6,330,000	6,530,000	4,810,000	4,230,000
2. Auxiliary equipment					
Ductwork	190,000	340,000	100,000	40,000	50,000
Fan system	700,000	390,000	180,000	270,000	200,000
Stack(s)	30,000	--	--	--	--
3. Installation					
Indirect costs	5,540,000	3,320,000	3,250,000	2,420,000	2,100,000
TOTAL ANNUAL COSTS	9,970,000	5,430,000	4,630,000	3,070,000	3,120,000
1. Direct costs	6,350,000	3,280,000	2,450,000	1,420,000	1,720,000
2. Indirect costs	3,620,000	2,150,000	2,180,000	1,650,000	1,390,000

TABLE 5-20. SUMMARY OF COSTS FOR HEPA FILTRATION SYSTEM
(Rounded Cost, 1988 $)

	Plant				
	FMC	Monsanto	Occidental	Stauffer, Montana	Stauffer, Tennessee
TOTAL CAPITAL INVESTMENT	4,200,000	2,870,000	1,610,000	620,000	1,020,000
1. Purchased equipment	1,300,000	800,000	500,000	190,000	310,000
2. Auxiliary equipment					
Ductwork	200,000	220,000	40,000	20,000	40,000
Fan system	370,000	250,000	170,000	70,000	100,000
Stack(s)	44,000	20,000	20,000	10,000	20,000
3. Installation					
Direct costs	1,380,000	950,000	530,000	200,000	340,000
Indirect costs	900,000	620,000	350,000	130,000	220,000
TOTAL ANNUAL COSTS	10,140,000	15,700,000	10,070,000	2,960,000	7,450,000
1. Direct costs	9,340,000	5,110,000	9,710,000	2,810,000	7,220,000
2. Indirect costs	800,000	590,000	360,000	150,000	230,000

5.4 REFERENCES FOR SECTION 5

1. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: FMC Plant, Pocatello, Idaho. Washington, D.C. June 1984.

2. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plants: Monsanto Plant, Soda Springs, Idaho. Washington, D.C. September 1984.

3. U. S. Environmental Protection Agency. Emissions of Lead-210 and Polonium-210 from Calciners at Elemental Phosphorus Plnats: Stauffer Plant, Silver Bow, Montana. Washington, D.C. August 1984.